

# Extended Ly $\alpha$ emission around quasars with eclipsing damped Ly $\alpha$ systems <sup>\*</sup>

H. Fathivavsari<sup>1</sup>, P. Petitjean<sup>1</sup>, P. Noterdaeme<sup>1</sup>, I. Pâris<sup>2</sup>, H. Finley<sup>3,4</sup>,  
S. López<sup>5</sup>, R. Srianand<sup>6</sup>

<sup>1</sup>*Institut d'Astrophysique de Paris, Université Paris 6-CNRS, UMR7095, 98bis Boulevard Arago, 75014 Paris, France*

<sup>2</sup>*Osservatorio Astronomico di Trieste, via G. B. Tiepolo 11, 34131 Trieste, Italy*

<sup>3</sup>*CNRS/IRAP, 14 Avenue E. Belin, F-31400 Toulouse, France*

<sup>4</sup>*University Paul Sabatier of Toulouse/ UPS-OMP/ IRAP, F-31400 Toulouse, France*

<sup>5</sup>*Departamento de Astronomía, Universidad de Chile, Casilla 36-D, Santiago, Chile*

<sup>6</sup>*Inter-University Centre for Astronomy and Astrophysics, Post Bag 4, Ganeshkhind, 411 007, Pune, India*

Accepted ..... Received .....

## ABSTRACT

We present spectroscopic observations of six high redshift ( $z_{\text{em}} > 2$ ) quasars, which have been selected for their Lyman  $\alpha$  (Ly $\alpha$ ) emission region being only partially covered by a strong proximate ( $z_{\text{abs}} \sim z_{\text{em}}$ ) coronagraphic damped Ly $\alpha$  system (DLA). We detected spatially extended Ly $\alpha$  emission envelopes surrounding these six quasars, with projected spatial extent in the range  $26 \leq d_{\text{Ly}\alpha} \leq 51$  kpc. No correlation is found between the quasar ionizing luminosity and the Ly $\alpha$  luminosity of their extended envelopes. This could be related to the limited covering factor of the extended gas and/or due to the AGN being obscured in other directions than towards the observer. Indeed, we find a strong correlation between the luminosity of the envelope and its spatial extent, which suggests that the envelopes are probably ionized by the AGN. The metallicity of the coronagraphic DLAs is low and varies in the range  $-1.75 < [\text{Si}/\text{H}] < -0.63$ . Highly ionized gas is observed to be associated with most of these DLAs, probably indicating ionization by the central AGN. One of these DLAs has the highest Al III/Si II ratio ever reported for any intervening and/or proximate DLA. Most of these DLAs are redshifted with respect to the quasar, implying that they might represent infalling gas probably accreted onto the quasar host galaxies through filaments.

**Key words:** quasars: absorption lines – quasars: emission lines - quasars: general

## 1 INTRODUCTION

The study of the gas associated with quasars, either in the disk or halo of the host galaxy is important in understanding the interplay between the AGN, its host-galaxy and the galactic environment. Linking the quasar host galaxy to the intergalactic medium (IGM), the circum-galactic medium (CGM) may provide fuel for star formation activities in the host galaxy. Indeed, gas from the IGM is being accreted along filaments through cold streams onto quasar host galaxies (Cantalupo et al. 2014; Martin et al. 2014).

In addition, the enrichment of the IGM by strong starburst-and/or AGN-driven outflows also occurs through the CGM gas (Adelberger et al. 2005; D’Odorico et al. 2013; Shull et al. 2015; Bordoloi et al. 2016). If strong enough, these outflows can expel a large fraction of gas from the CGM into the IGM and consequently suppress further star formation in the galaxy (Silk & Rees 1998; Maiolino et al. 2012). Observing the CGM around high redshift quasars will hence offer important insights into the so-called ‘AGN feedback’ in galaxy formation and evolution.

For decades, the preferred observational technique for studying the CGM has been the analysis of absorption lines detected in the spectra of background quasars (Bahcall & Spitzer 1969; Petitjean et al. 1996b; Croft et al. 2002; D’Odorico et al. 2002; Bergeron et al. 2004; Hennawi et al. 2006; Hennawi & Prochaska 2007; Steidel et al. 2010;

<sup>\*</sup> Based on data obtained with MagE at the Clay telescope of the Las Campanas Observatory (CNTAC Prgm. ID CN2012B-51 and CN2013A-121) and with XSHOOTER at the ESO/VLT in Chile as a part of ESO program 091.A-0299(A).

Churchill et al. 2013; Landoni et al. 2016; Péroux et al. 2016; Quiret et al. 2016). This observational technique revealed the presence of infalling and outflowing absorbing material around high redshift galaxies (Steidel et al. 2000; Simcoe, Sargent & Rauch 2004; Bouché et al. 2007; Ryan-Weber et al. 2009; Rubin et al. 2012; Shull, Danforth & Tilton 2014). While most of the studies used quasars as background sources, the method has been extended to using galaxies (e.g. Steidel et al. 2010) as well as GRBs (e.g. Petitjean & Vergani 2011) as background sources. However, the one dimensional nature of this method does not allow one to map the spatial distribution of these material around an individual galaxy.

Alternatively, detecting the CGM in emission (e.g. Ly $\alpha$ ) around high redshift quasars could in principle provide information on the spatial distribution of the gas surrounding the quasar host galaxies (see Cantalupo et al. 2014; Hennawi et al. 2015). Indeed, extended Ly $\alpha$  emission have been found around high redshift ( $z > 2$ ) quasars, extending up to distances as large as 100–200 kpc with typical luminosity of  $10^{43}$  erg s $^{-1}$  (Hu & Cowie 1987; Petitjean et al. 1996a; Lehnert & Becker 1998; Heckman et al. 1991a,b; Christensen et al. 2006, hereafter CJ06; Courbin et al. 2008; North et al. 2012, hereafter NC12; Borisova et al. 2016). In an effort to study extended Ly $\alpha$  emission around high redshift quasars, Arrigoni Battaia et al. (2016) obtained 15 deep ( $\sim 2.0 \times 10^{-18}$  erg s $^{-1}$  cm $^{-2}$  arcsec $^{-2}$ ) narrow band images of  $z_{\text{em}} \sim 2.25$  quasars, using GMOS on Gemini-South telescope. They detect Ly $\alpha$  emission around half of their quasars, extending up to 32 kpc with a surface brightness in excess of  $10^{-17}$  erg s $^{-1}$  cm $^{-2}$  arcsec $^{-2}$ . Several mechanisms have been proposed to power this emission: photo-ionization by the photons emitted by an AGN and/or a starburst region (Weidinger, Möller & Fynbo 2004; Weidinger et al. 2005), ionization induced by the shock waves from radio jets (e.g. Heckman et al. 1991a,b), and cooling radiation after the gravitational collapse (a.k.a cold accretion, Haiman et al. 2000; Yang et al. 2006).

In the ‘cold accretion’ scenario, a spatially extended distribution of infalling cold gas collapses into the potential wells of dark matter and gets heated. The heat is then dissipated through the emission of Ly $\alpha$  photons. The resulting line radiation could potentially be observed as extended, low surface brightness Ly $\alpha$  ‘fuzz’ around high redshift quasars (Haiman et al. 2000; Fardal et al. 2000). Based on hydrodynamical simulations of galaxy formation, Dijkstra & Loeb (2009) showed that this infall of primordial gas into the centers of dark matter haloes could explain the observed Ly $\alpha$  emission if only  $\gtrsim 10\%$  of the gravitational potential energy is converted into the Ly $\alpha$  radiation. Here, the emission would come from the filamentary cold streams of metal-poor intergalactic gas. The gas is optically thick and self-shielded against external ionizing radiation sources and therefore the emission would not depend on the presence of a central AGN or a starburst region. Haiman & Rees (2001), on the other hand, estimated that if a central quasar is switched on inside a collapsing primordial gas, this could significantly enhance the Ly $\alpha$  emission of the cloud. They predict angular diameter of a few arcseconds and surface brightness  $\sim 10^{-18}$  to  $10^{-16}$  erg s $^{-1}$  cm $^{-2}$  arcsec $^{-2}$  for the Ly $\alpha$  fuzz. This surface brightness would be detectable with current telescopes through spectroscopy or deep narrow-band imag-

ing (Steidel et al. 1991; Fried 1998; Bergeron et al. 1999; Fynbo et al. 2000; Bunker et al. 2003). Confirming the prediction by Haiman & Rees (2001), Weidinger et al. (2004) found low metallicity primordial material falling onto the AGN through the ionizing cone of the quasar, causing the gas to glow in Ly $\alpha$  due to recombination. Moreover, Jiang et al. (2016) found a strong narrow Ly $\alpha$  emission line in the trough of a proximate-DLA (PDLA) towards the quasar SDSS J0952+0114; and they argued that this Ly $\alpha$  emission is most likely originated from some large scale outflowing material driven by the central AGN.

It may well be that the spatially extended Ly $\alpha$  fuzz seen around a high redshift galaxy (hosting a quasar) is powered by more than one powering mechanism at the same time. It is also possible that both infall and outflow of material are occurring simultaneously in the CGM of a single galaxy. Using integral field spectroscopy to study the giant Ly $\alpha$  nebula around a high redshift radio galaxy at  $z = 4.11$ , Swinbank et al. (2015) found two blueshifted (with respect to the systemic redshift of the galaxy) H I absorbers with covering fraction  $\sim 1$  against the Ly $\alpha$  emission. They argued that the more blue-shifted absorber, showing dynamics similar to that of the emitting gas, is part of an expanding shell of gas that surrounds the Ly $\alpha$  emission nebula. They then suggested that the emission nebula itself is probably powered by the cooling of primordial gas inside a dark matter halo. In principle, combining the information from both the 1D and 2D spectra of an Ly $\alpha$  emission envelope would allow one to determine which powering mechanism is at play (Weidinger et al. 2005).

With the aim of accessing spatially extended Ly $\alpha$  emission regions around high redshift quasars, we recently searched the SDSS-III Baryon Oscillation Spectroscopic Survey (BOSS; Dawson et al. 2013) for strong damped Ly $\alpha$  absorption systems (DLAs;  $\log N_{\text{HI}} > 21.30$ ) coincident in redshift with the quasar (Finley et al. 2013). Each of these ‘eclipsing DLAs’, plays the role of a natural coronagraph, completely extinguishing the broad Ly $\alpha$  emission from the quasar, revealing some narrow Ly $\alpha$  emission line in its trough (Hennawi et al. 2009; Finley et al. 2013; Fathivavsari et al. 2015, hereafter paper I; Jiang et al. 2016). This narrow emission line originates from a source located at approximately the same redshift as the quasar and possibly physically associated with it. Ly $\alpha$  emission from the quasar narrow line region (NLR), or from star-forming regions in the quasar host galaxy, and Ly $\alpha$  emitting haloes around the quasar could be responsible for this narrow Ly $\alpha$  emission line seen in the DLA trough.

In Finley et al. (2013), we found 26 quasars with  $z > 2$ , showing narrow Ly $\alpha$  emission line in the trough of their eclipsing DLAs. We then performed follow-up observations of six of these systems using the Magellan-MagE echelle spectrograph in order to gain insight into the origin of their extended emission. One of these six objects (i.e. J0823+0529) was already studied in detail in paper I and the remaining objects are covered in this paper.

Observations and data reduction are described in section 2. The properties of individual objects are discussed in section 3. Results are given in section 4, and section 5 presents the conclusions. In this work, we use a standard flat  $\Lambda$ CDM cosmology with  $\Omega_{\Lambda} = 0.73$ ,  $\Omega_m = 0.27$ , and  $H_0 = 70$  km s $^{-1}$  Mpc $^{-1}$  (Komatsu et al. 2011).

**Table 1.** Journal of MagE observations.

QSO	Date	Exp. time(s)	Seeing(")	Slit width(")
		(EW/NS)	(EW/NS)	(EW/NS)
J0112–0048	2012-12-13	3600/3600	1.1/1.0	1.0/1.0
J0953+0349	2013-02-13	3600/3600	1.2/1.1	0.85/0.85
J1058+0315	2013-02-13	3600/3600	1.2/1.0	1.0/0.85
J1154–0215	2012-01-22	3017/3600	0.9/0.9	1.0/1.0
J1253+1007	2013-02-13	2700/3600	1.0/1.2	1.0/1.0

## 2 OBSERVATIONS AND DATA REDUCTION

In the course of a survey for DLA systems having redshifts coincident with the redshift of the quasar (eclipsing DLAs), we found 26 quasars that exhibit Ly $\alpha$  emission at the bottom of their eclipsing DLAs (Finley et al. 2013). We then performed follow-up echelle spectroscopy of six of these quasars using the Magellan Echelle spectrograph (MagE; Marshall et al. 2008) on the 6.5 m Clay telescope located at Las Campanas observatory in Chile. The spectrograph is equipped with 10 arcsec long slits of various widths and has a medium resolution ( $R \sim 4000$ ), covering the full visible spectral range (3000 to 10 000 Å). For one of the quasars (i.e. J0953+0349), we also have an XSHOOTER spectrum (as a part of ESO program 091.A-0299(A)). The XSHOOTER spectrograph (Vernet et al. 2011), mounted on the Very Large Telescope (VLT), covers the full spectral region from 3000 Å to 2.5  $\mu$ m and has a resolution of  $R \sim 5300$  in the near-infrared (NIR) arm when the slit width is 0.9 arcsec.

The MagE observations were performed by keeping the slit along two perpendicular position angles, namely along north-south and east-west directions. The observations were done in the ‘derotator’ mode in order to fix the position angles during each exposure time. The journal of the observations is shown in Table 1. For each quasar, the spectrum of a standard star was also obtained, immediately after the science exposure, to allow for a precise flux calibration of the quasar spectra. The spectra were reduced and extracted using the *MagE\_Reduce* pipeline written and developed by George Becker<sup>1</sup>. Since the spectral orders of the observed spectra are curved with respect to the (x,y)-coordinate system defined by the CCD columns and rows (Kelson 2003), we followed the method described in paper I to rectify the curvature of the orders. The final spectra are then binned with a  $3 \times 3$  box, resulting in  $\text{FWHM} = \sim 80 \text{ km s}^{-1}$ . Each pixel has a width of  $\sim 27 \text{ km s}^{-1}$ , and each spectral resolution element is sampled by 3 pixels. Each pixel along the slit covers  $\sim 0.3$  arcsec. The pipeline uses optimum sky subtraction techniques (Kelson 2003) to subtract the background emission from the 2D spectra. We also checked that the residual flux outside the quasar trace at  $\sim 100$  Å away on either side of the extended Ly $\alpha$  emission is consistent with the background noise levels. Therefore, the background subtraction has minimum effect on the extent of the envelopes in our sample.

## 3 NOTES ON INDIVIDUAL OBJECTS

For each quasar, we determine its systemic redshift,  $z_{\text{em}}$  (using quasar’s intrinsic emission lines like He II, H $\beta$ , C IV, ..., etc), the redshift of the eclipsing DLA,  $z_{\text{abs}}$  (using simultaneous fit of some low ion species), and the redshift of the Ly $\alpha$  emission ( $z_{\text{Ly}\alpha}$ ) seen in the trough of the eclipsing DLA. The parameters are listed in Table 2. In this table, columns 8 and 9 are the velocity widths of the Ly $\alpha$  emission ( $\Delta V_{\text{Ly}\alpha}$ ) and of the C IV absorption features ( $\Delta V_{\text{CIV}}$ ), respectively. The Ly $\alpha$  emission (resp. C IV absorption) velocity width is defined as the wavelength region over which the flux level (resp. optical depth) is larger than the  $1\sigma$  detection limit. Using *VPFIT*<sup>2</sup>, we fit the low and high ion species associated with the eclipsing DLAs and then determine the metallicity of the absorbers when possible. To fit the absorption lines we used the same techniques described in Fathivavarsari et al. (2013). The plots showing the 1D and 2D emission spectra along with the fits to the absorption lines for the quasar J0112–0048 are presented in Figs. 1 & 2 while the corresponding plots of the remaining quasars are shown in Appendix A. The parameters of the fits are summarized in Tables 3 & 4. In Table 3, the values in brackets are uncertain because either the corresponding absorption lines are affected by noise or all lines are strongly saturated. The metallicity and relative abundances given in the last two rows of Table 3 are obtained using solar photospheric abundances from Asplund et al. (2009).

In all quasar spectra, the Ly $\alpha$  emission detected in the trough of the DLA is observed to be spatially extended. One can think of this Ly $\alpha$  emission as a combination of two components: the spatially unresolved narrow Ly $\alpha$  emission (located on the quasar trace) and the second component which extends beyond the quasar trace. The quasar trace is defined by the point spread function (PSF) of the quasar continuum close to the wavelength range where the Ly $\alpha$  emission is detected. The FWHM of the PSF ( $\sim 1$  arcsec) is approximately 8 kpc at the relevant redshift. To determine the flux of the extended emission, we first need to subtract the contribution from the unresolved component of the emission which is seen on the quasar trace. To do so, we follow the method described in section 5 of paper I. Throughout this paper, by envelope luminosity we mean the luminosity of the Ly $\alpha$  emission after subtracting that along the quasar trace. The Ly $\alpha$  flux and luminosity of the extended envelopes, their spatial extent, and their mean surface brightness are listed in Tables 5 & 6.

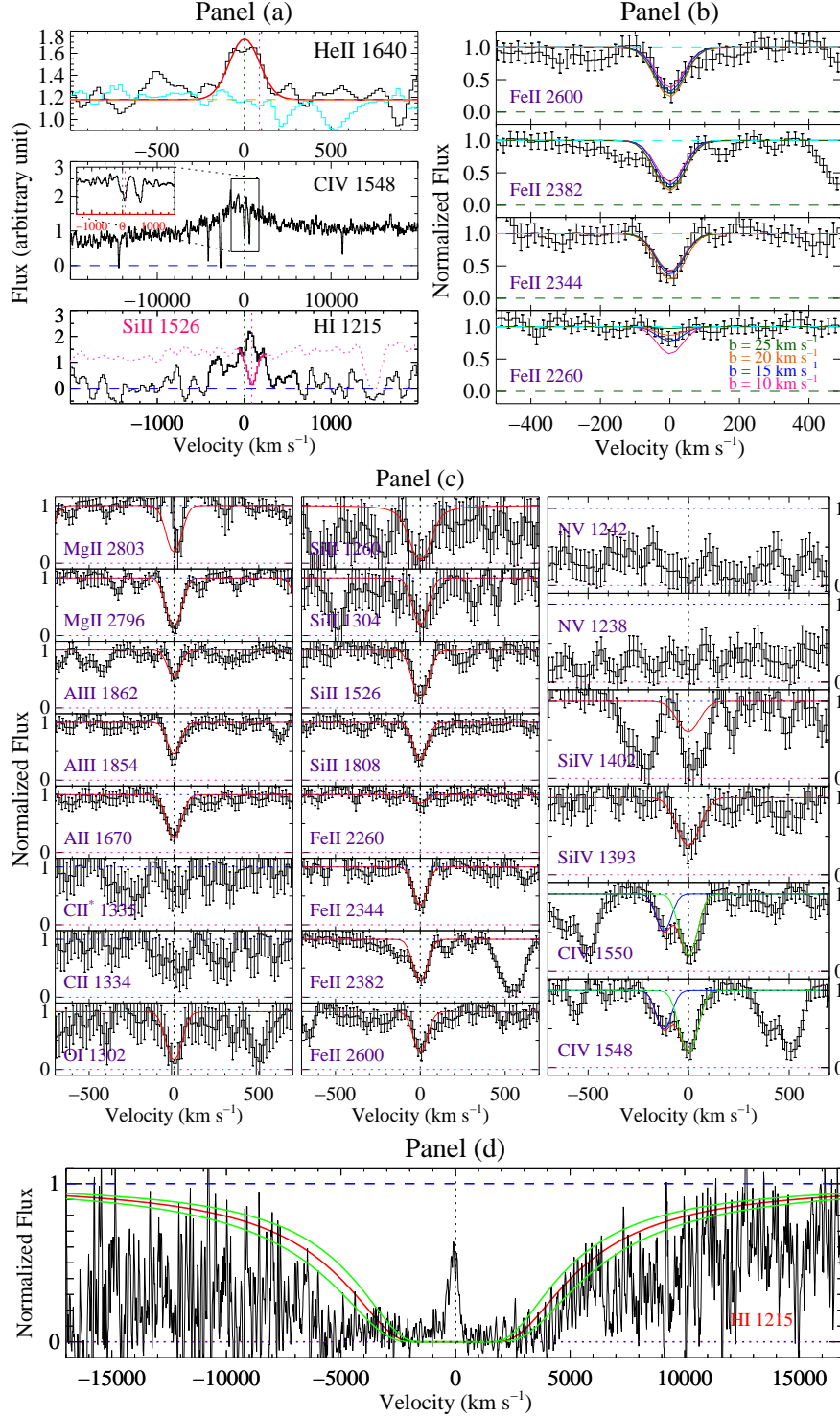
We emphasize that the extent of an envelope along the north, south, east, or west direction is defined as the distance (in arcsecond or kpc) from the center of the quasar trace up to the spatial pixel at which the flux density per square arcsec reaches below the  $1\sigma$  detection limit. The  $1\sigma$  uncertainty in the flux for each PA is reported in the sixth column of Table 5.

### 3.1 SDSS J011226.76–004855.8

For this quasar we detect Ly $\alpha$ , C IV, and He II emission lines. To estimate the quasar redshift, we have fitted a Gaus-

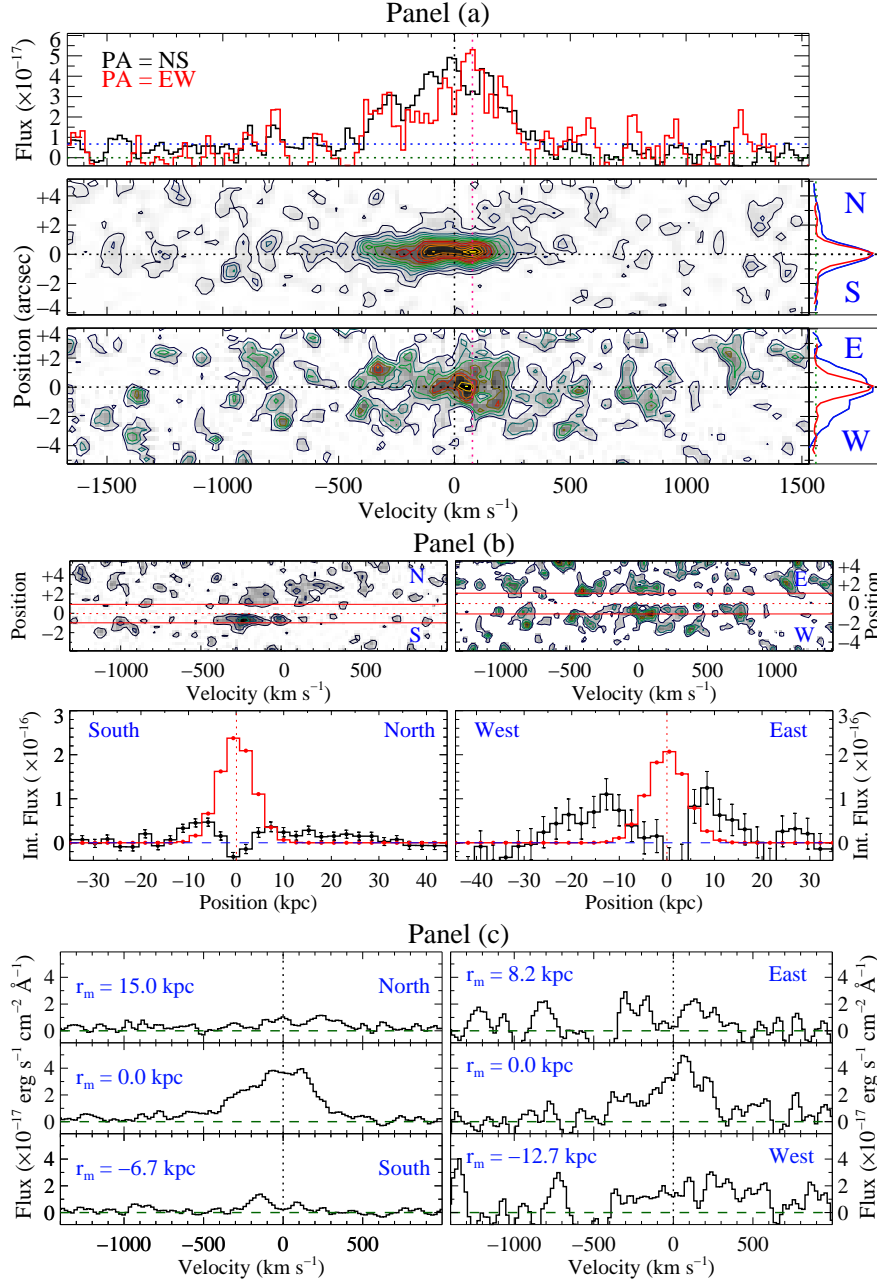
<sup>1</sup> [ftp://ftp.ast.cam.ac.uk/pub/gdb/mage\\_reduce/](ftp://ftp.ast.cam.ac.uk/pub/gdb/mage_reduce/)

<sup>2</sup> <http://www.ast.cam.ac.uk/~rfc/vpfit.html>



**Figure 1.** *Panel (a):* Velocity profiles of some emission lines detected in the spectrum of the quasar J0112-0048. The adopted systemic redshift of the quasar ( $z_{\text{em}} = 2.1485$ ) is used as the origin of the velocity scale. The sky spectrum is overplotted as a cyan curve in the top sub-panel. The pink vertical dotted lines mark the redshift of the low-ion species. Note that in the HI emission line sub-panel, we overplot the Si II  $\lambda 1526$  absorption as a pink curve. The inset in the middle sub-panel shows a close-up view of the CIV emission line region. *Panel (b):* The optical depths of several Fe II transitions are used to constrain the Doppler parameter. The best fits for different Doppler parameters are indicated by different colors. *Panel (c):* Velocity plots and VPFIT solutions (where applicable) of the species detected in the DLA at  $z_{\text{abs}} = 2.1493$ . As shown in the CIV doublet panel, the CIV absorption has an additional weaker component at  $v = -117 \text{ km s}^{-1}$ . For the low-ion species, we assume  $b = 17.4 \text{ km s}^{-1}$  as found from the analysis shown in Panel (b). *Panel (d):* the red curve is the single component fit to the damped Ly $\alpha$  absorption profile with the two green curves showing the  $\pm 1 \sigma$  uncertainty.





**Figure 2.** 1D and 2D spectra around the Ly $\alpha$  emission of quasar J0112-0048. *Panel (a)*: this panel comprises of three sub-panels. The zero velocity is at  $z_{\text{em}} = 2.1485$  and the position of the DLA (at  $z_{\text{abs}} = 2.1493$ ) is shown as a vertical pink dotted line in the three sub-panels. The upper sub-panel shows the 1D spectra of the Ly $\alpha$  emission seen at the bottom of the DLA trough for the two PAs. The green and blue horizontal dotted lines show the zero flux level and the  $1\sigma$  uncertainty on the flux, respectively. Here, the y-axis is in the unit of  $\text{erg s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}$ . The middle and lower sub-panels show the 2D spectra of the Ly $\alpha$  emission seen in the DLA trough for the two PAs. The outermost contour along PA=NS (resp. PA=EW) corresponds to a flux density of  $1.83 \times 10^{-19}$  (resp.  $9.13 \times 10^{-20}$ )  $\text{erg s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}$  and each contour is separated by  $1.83 \times 10^{-19}$  (resp.  $9.13 \times 10^{-20}$ )  $\text{erg s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}$  from its neighboring contour. The black horizontal dotted lines mark the center of the quasar trace. Panels on the right show the spatial profiles integrated over the whole spectral width of the Ly $\alpha$  emission (blue curves). The red curves show the profile of the quasar continuum PSF. *Panel (b)*: this panel comprises of two upper sub-panels and two lower sub-panels. The upper sub-panels show the 2D spectra of the Ly $\alpha$  emission after subtracting the quasar trace for the two PAs. The contour levels are the same as in panel (a). The center of the trace is marked by the red horizontal dotted line and the full width of the trace (i.e.  $2 \times \text{FWHM}$ ) is shown by the red solid horizontal lines. The y-axis here is position in arcsecond. The lower sub-panels show the spatial profiles of the extended Ly $\alpha$  emission (black histogram) and that of the quasar trace (red histogram). Here, the y-axis is in  $\text{erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}$ . *Panel (c)*: velocity profiles of the spatially extended Ly $\alpha$  emission at several distances from the AGN. The parameter  $r_m$  indicates the mean distance to the central AGN.

sian function to the He II emission line which resulted in  $z_{\text{em}} = 2.1485$  (see panel (a) of Fig. 1). We adopt this value as the systemic redshift of the quasar.

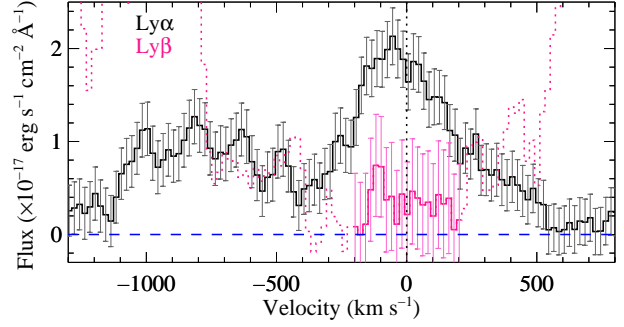
Associated to the eclipsing DLA along this line of sight, we detect absorption from low and high ionization species like, O I, C II, Al II, Al III, Mg II, Fe II, Si II, Si IV, and C IV. As shown in panel (c) of Fig. 1, the low-ion absorption profiles are dominated by a single component at  $z_{\text{abs}} = 2.1493$ . The DLA is located at  $v \sim +76 \text{ km s}^{-1}$  relative to the quasar. We used several Fe II transitions (i.e. Fe II  $\lambda 2600$ , 2382, 2344, and 2260) to constrain the Doppler parameter of this component. In panel (b) of Fig. 1, the VPFIT solutions for different Doppler parameters are shown by different colors.

The fact that Fe II  $\lambda 2260$  is detected and is not saturated allows us to constrain the Doppler parameter. As shown in panel (b) of Fig. 1, the best fit of the four Fe II transitions results in  $b = 17.4 \text{ km s}^{-1}$ . To determine the H I column density of the DLA, a single component fit was conducted to the DLA trough with the redshift fixed to the value derived from the low-ion species, i.e.  $z_{\text{abs}} = 2.1493$ , and we obtained  $\log N_{\text{HI}} = 21.95 \pm 0.10$ . The fit is shown in panel (d) of Fig. 1 as a red curve overplotted on the observed spectrum (black curve), with the two green curves indicating the corresponding  $\pm 1\sigma$  uncertainty. The fit to other low-ion species was performed by fixing their corresponding Doppler parameter and redshift to those obtained for Fe II. The C IV and Si IV doublets were fitted independently with all parameters allowed to vary during the fitting process. The parameters of the fit are listed in Tables 3 & 4. As shown in panel (c) of Fig. 1, the expected position of the NV doublet falls on the red wing of the strong DLA profile and is probably lost in the noise. The Si IV  $\lambda 1402$  absorption profile is also blended with some unidentified features. The C IV doublet has two absorption components located at  $v \sim +5$  and  $-117 \text{ km s}^{-1}$  relative to  $z_{\text{abs}}$ . While the component at  $v \sim +5$  is also seen in Si IV, the second component is only detected in C IV, and no low-ion absorption is associated with this second component.

As shown in Fig. 2, the Ly $\alpha$  emission at the center of the DLA trough is spatially extended along both PAs. Along the north-south (NS) direction, the emission is more extended to the north up to  $\sim 3.5$  arcsec (30 kpc) while the extension to the south reaches up to  $\sim 1.6$  arcsec (13.5 kpc) away from the quasar trace. Along the east-west direction, the emission seems to be more extended to the west ( $\sim 3$  arcsec or 25.5 kpc) than to the east ( $\sim 2$  arcsec or 16.5 kpc). The Ly $\alpha$  flux and luminosity of the envelope, its angular size, and the mean surface brightness are listed in Tables 5 & 6.

From panel (c) of Fig. 2, one can see that the Ly $\alpha$  emission on the quasar trace is asymmetric, with a steeper drop of the flux in its red wing and a shallower rise in the blue wing. This asymmetry is less prominent along the east-west (EW) direction due to the high level of noise. Since the emission seen on the trace is not resolved, one would expect the same spectrum for the quasar trace, regardless of the slit orientation. As illustrated in panel (c) of Fig. 2, the spectra on the trace for the two PAs are consistent within the errors.

The Ly $\alpha$  emitting (resp. absorbing) gas is  $\sim 29 \text{ km s}^{-1}$  (resp.  $\sim 76 \text{ km s}^{-1}$ ) blueshifted (resp. redshifted) relative to the systemic redshift of the quasar. These low velocity differences hint at the possibility that the emitting and/or ab-



**Figure 3.** Ly $\alpha$  (black curve) and Ly $\beta$  (pink curve) emission lines detected in the trough of the damped Ly $\alpha$  and Ly $\beta$  absorption lines along the line of sight towards the quasar J1253+1007.

sorbing cloud may originate from somewhere in the quasar host galaxy or its close vicinity.

### 3.2 SDSS J095307.13+034933.8

This is the only quasar for which we also have an XSHOOTER spectrum. Unfortunately, the SNR of this spectrum in the regions where we expect to see redshifted Mg II, [O II] and [O III] emission lines is not very high because the lines are either located in bad portions of the spectrum or spoiled by strong sky lines. However, we could still use the H $\beta$  emission line to get an emission redshift of  $z_{\text{em}} = 2.5940$  (see Fig. A1). We adopt this redshift as the systemic redshift of the quasar. As shown in Fig. A1, we also detect O I  $\lambda 1304$ , C III]  $\lambda 1909$ , Si III]  $\lambda 1892$ , and C IV  $\lambda 1548$  emission lines in the MagE spectrum of this quasar. Fitting Gaussians to these emission lines yields  $z = 2.5930$ , 2.5883, 2.5915, and 2.5880, respectively. The emission redshift from O I  $\lambda 1304$  and Si III]  $\lambda 1892$  are consistent with that obtained from H $\beta$  within  $200 \text{ km s}^{-1}$ . But C III] and C IV emission lines show, respectively, 475 and  $500 \text{ km s}^{-1}$  blue-shift with respect to the adopted systemic redshift of the quasar.

We fit a single Gaussian to the low ionization lines to get the redshift  $z_{\text{abs}} = 2.5961$  of the eclipsing DLA along this line of sight which is  $175 \text{ km s}^{-1}$  redshifted with respect to the quasar. We fit the Ly $\alpha$  trough with a Voigt profile and derived  $\log N_{\text{HI}} = 21.95 \pm 0.10$ . We detect absorption from O I, C II, Si II, Al II, Fe II in one component (see Fig. A1). To constrain the corresponding Doppler parameter, we follow the same procedure described in the previous section. As demonstrated in panel (b) of Fig. A1, Doppler parameters less than  $20 \text{ km s}^{-1}$  (pink and blue curves) are clearly excluded while larger Doppler parameters (i.e.  $b > 25 \text{ km s}^{-1}$ ) are consistent with the observations. Therefore, our reported column densities and metallicity should be considered as upper limits. Parameters of the fit are reported in Tables 3 & 4, and the metallicity of the system is  $[\text{Si}/\text{H}] < -1.75 \pm 0.20$ .

It is interesting to note that strong low ionization components (O I and C II, C II\*) are also seen at  $z = 2.5882$  ( $660 \text{ km s}^{-1}$  blueshifted with respect to the DLA). The C IV and Si IV absorption associated with this component is strong and spread over  $\sim 250 \text{ km s}^{-1}$ . NV may also be present but it seems to be strongly blended with some intervening absorption.

As shown in Fig. A2, the Ly $\alpha$  emission at the bottom of the DLA absorption line is extended along both PAs. From

**Table 2.** The redshifts of the quasar, the Ly $\alpha$  emission, and the DLA are given in columns 2 to 4 and the corresponding velocity separations are in columns 5 to 7. The values in columns 5 and 6 are with respect to the quasar’s adopted systemic redshift while the values in column 7 are relative to the DLA redshift, i.e.  $z_{\text{abs}}$ . Columns 8 and 9 give the velocity widths of the extended Ly $\alpha$  emission and the C IV absorption profile where the signal is more than the  $1\sigma$  detection limit. Note that all velocities are in  $\text{km s}^{-1}$ . The last column gives the upper limit (in pc) on the size of the H I cloud derived by assuming that the hydrogen number density in our eclipsing DLAs is  $n_{\text{H}} > 10 \text{ cm}^{-3}$  (see section 4.6.2).

ID	$z_{\text{em}}$	$z_{\text{Ly}\alpha}$	$z_{\text{abs}}$	$\delta V_{\text{DLA-QSO}}$	$\delta V_{\text{Ly}\alpha\text{-QSO}}$	$\delta V_{\text{Ly}\alpha\text{-DLA}}$	$\Delta V_{\text{Ly}\alpha}$	$\Delta V_{\text{CIV}}$	$l(\text{H I})$
J0112–0048	2.1485	2.1482	2.1493	+76	–29	–105	800	320	< 289
J0823+0529	3.1875	3.1925	3.1910	+250	+358	–107	1400	754	< 10 <sup>a</sup>
J0953+0349	2.5940	2.5929	2.5961	+175	–92	–267	1222	837	< 289
J1058+0315	2.3021	2.3029	2.2932	–809	+73	+882	520	240	< 204
J1154–0215	2.1810	2.1842	2.1853	+405	+301	–103	1157	1064	< 182
J1253+1007	3.0150	3.0308	3.0312	+1207	+1177	–30	1560	1030	< 65

<sup>a</sup> See paper I.

**Table 3.** Column densities and metallicities of the low-ionization species detected in the eclipsing DLAs. The values in brackets are uncertain because either the corresponding absorption lines are affected by noise or all lines are strongly saturated. Column densities are given in logarithmic units.

	J0112–0048	J0823+0529	J0953+0349	J1058+0315	J1154–0215	J1253+1007
$b^a$	17.4	20.0	20.0	15.0	20.0	37.0
N(O I)	[17.47 $\pm$ 0.24]	[17.08 $\pm$ 0.50]	[17.11 $\pm$ 0.20]	.....	.....	16.04 $\pm$ 0.10
N(Si II)	16.83 $\pm$ 0.14	16.42 $\pm$ 0.10	15.71 $\pm$ 0.10	15.90 $\pm$ 0.20	15.55 $\pm$ 0.20	15.36 $\pm$ 0.10
N(Fe II)	15.05 $\pm$ 0.20	15.33 $\pm$ 0.20	15.43 $\pm$ 0.20	15.74 $\pm$ 0.15	15.35 $\pm$ 0.20	14.27 $\pm$ 0.10
N(C II)	.....	.....	[17.11 $\pm$ 0.20]	.....	.....	[16.12 $\pm$ 0.20]
N(C II*)	.....	.....	[15.70 $\pm$ 0.20]	.....	.....	[14.80 $\pm$ 0.20]
N(Al II)	[14.77 $\pm$ 0.20]	.....	[14.09 $\pm$ 0.15]	[15.56 $\pm$ 0.16]	[15.30 $\pm$ 0.30]	[13.69 $\pm$ 0.10]
N(Al III)	13.91 $\pm$ 0.10	14.80 $\pm$ 0.10	13.65 $\pm$ 0.10	13.36 $\pm$ 0.10	15.20 $\pm$ 0.30	13.14 $\pm$ 0.10
N(Mg II)	[15.90 $\pm$ 0.25]	.....	.....	16.96 $\pm$ 0.20	[15.30 $\pm$ 0.30]	.....
N(H I)	21.95 $\pm$ 0.10	21.70 $\pm$ 0.10	21.95 $\pm$ 0.10	21.80 $\pm$ 0.10	21.75 $\pm$ 0.10	21.30 $\pm$ 0.10
[Si/H]	–0.63	–0.79	–1.75	–1.41	–1.71	–1.45
[Si/Fe]	1.77	1.08	0.27	0.15	0.19	1.08

<sup>a</sup> Doppler parameter ( $\text{km s}^{-1}$ ), see the text.

this figure, we can see that the Ly $\alpha$  envelope is spatially asymmetric. The emission extends out to a maximum distance of  $\sim 2.4 \text{ arcsec}$  (20 kpc) and  $\sim 1.9 \text{ arcsec}$  (16 kpc) in the south and east directions, respectively. Note that the emission towards the north is so weak that we take it as a tentative detection.

The spectra of the quasar trace for the two PAs are consistent with each other within the errors (see panel (c) of Fig. A2). The DLA is redshifted by  $\sim 175 \text{ km s}^{-1}$  relative to the systemic redshift of the quasar while the Ly $\alpha$  envelope and the second low-ion system (located at  $z_{\text{abs}} = 2.5882$ ) are both blueshifted compared to  $z_{\text{em}}$  by 92 and  $484 \text{ km s}^{-1}$ , respectively. It seems possible that the low metallicity DLA ( $[\text{Si}/\text{H}] < -1.75$ ) is infalling towards the central AGN and that the second low-ion system is part of some outflowing material. It is also possible that both the absorption and emission originate from the same structure. Note that the transverse extensions of both of the two absorbing clouds should be small compared to the NLR.

### 3.3 SDSS J105823.73+031524.4

In addition to Ly $\alpha$ , we detect emission from C III], C IV, and He II in the spectrum of this quasar (see Fig. A3). The C III]  $\lambda 1909$  emission line falls on top of a strong sky emission line at  $6300 \text{ \AA}$  and hence cannot yield a reliable redshift estimate. On the other hand, the blue wing of the He II  $\lambda 1640$  emission line is affected by noise. However, we could still use the red wing of the profile to carefully constrain the fit and obtain  $z_{\text{em}} = 2.3021$  which was adopted as the systemic redshift of the quasar. Interestingly, the C IV emission line indicates a similar redshift.

The broad Ly $\alpha$  emission line of this quasar is extinguished by the presence of a strong DLA located at  $z_{\text{abs}} = 2.2932$  (derived through simultaneous fit of the low ionization species) which is  $\sim 810 \text{ km s}^{-1}$  blue-shifted relative to the quasar systemic redshift. The H I column density of  $\log N_{\text{HI}} = 21.80 \pm 0.10$  is derived from a single component fit to the DLA profile (see panel (d) of Fig. A3). This DLA is associated with a number of low and high ionization species including O I, C II, Si II, Fe II, Al II, Al III, Mg II, Si IV and C IV (see Fig. A3). The somewhat low SNR of the spectrum does not allow us to uniquely constrain the Doppler parameter

**Table 4.** Column densities of high ionization species. Note that the second column gives the velocity separation of that component with respect to the strongest component in the low-ion species (see Table 2).

$z$	$\delta V(\text{km s}^{-1})$	Ion(X)	$b(\text{km s}^{-1})$	$\log N(\text{X})$
SDSS J0112-0048				
2.148066	-117.5	C IV	$10.0 \pm 2.0$	$15.67 \pm 0.30$
2.149356	+5.3	C IV	$16.7 \pm 5.0$	$16.70 \pm 0.30$
2.149338	+3.6	Si IV	$56.1 \pm 4.0$	$13.86 \pm 0.20$
SDSS J0953+0349				
2.585898	-851.7	C IV	$22.2 \pm 9.0$	$14.24 \pm 0.24$
2.588245	-665.6	C IV	$68.8 \pm 7.7$	$15.06 \pm 0.04$
2.590421	-473.8	C IV	$62.5 \pm 24.0$	$15.04 \pm 0.12$
2.591778	-360.5	C IV	$10.0 \pm 5.0$	$15.72 \pm 0.30$
2.593449	-221.1	C IV	$40.0 \pm 8.7$	$14.00 \pm 0.04$
2.595836	-22.0	C IV	$41.9 \pm 5.4$	$14.65 \pm 0.05$
2.588187	-660.4	Si IV	$26.4 \pm 7.0$	$14.92 \pm 0.30$
2.589003	-592.2	Si IV	$13.0 \pm 5.0$	$13.30 \pm 0.30$
2.590254	-487.8	Si IV	$34.3 \pm 14.0$	$13.90 \pm 0.20$
2.595963	-11.4	Si IV	$29.0 \pm 7.8$	$14.36 \pm 0.21$
SDSS J1058+0315				
2.293476	+34.2	C IV	$37.4 \pm 5.0$	$14.93 \pm 0.20$
2.293406	+27.8	Si IV	$24.4 \pm 2.3$	$15.50 \pm 0.30$
SDSS J1154-0215				
2.177275	-756.3	C IV	$84.8 \pm 5.3$	$14.83 \pm 0.10$
2.178558	-635.2	C IV	$74.6 \pm 14.1$	$14.71 \pm 0.20$
2.185181	-11.2	C IV	$46.4 \pm 3.3$	$14.98 \pm 0.20$
SDSS J1253+1007				
3.022167	-672.5	C IV	$60.4 \pm 2.2$	$14.95 \pm 0.05$
3.025153	-450.0	C IV	$15.0 \pm 2.0$	$13.75 \pm 0.11$
3.027819	-251.5	C IV	$40.0 \pm 5.0$	$16.20 \pm 0.13$
3.029663	-114.3	C IV	$35.0 \pm 5.0$	$14.10 \pm 0.15$
3.031250	+3.7	C IV	$33.0 \pm 2.0$	$15.70 \pm 0.10$
3.032776	+117.2	C IV	$30.0 \pm 3.0$	$13.30 \pm 0.10$
3.021977	-686.7	Si IV	$93.6 \pm 12.0$	$13.30 \pm 0.10$
3.027811	-252.1	Si IV	$45.8 \pm 2.0$	$14.55 \pm 0.10$
3.031253	+4.0	Si IV	$53.5 \pm 2.0$	$14.54 \pm 0.10$
3.021785	-701.0	N V	$40.2 \pm 4.0$	$15.23 \pm 0.12$
3.023130	-600.7	N V	$11.9 \pm 4.5$	$14.73 \pm 0.20$
3.027967	-240.5	N V	$39.4 \pm 2.5$	$14.80 \pm 0.10$

using several transitions of the same species. However, we still used four Fe II transitions to derive a lower limit on this parameter,  $b > 15 \text{ km s}^{-1}$  (see panel (b) of Fig. A3). We derive iron and silicon abundances of  $[\text{Fe}/\text{H}] < -1.56 \pm 0.20$  and  $[\text{Si}/\text{H}] < -1.41 \pm 0.20$ .

Independent fits to the C IV and Si IV absorption lines were conducted with one main component (see Fig. A3). A Gaussian fit to the Ly $\alpha$  emission line gives  $z_{\text{Ly}\alpha} = 2.3029$  which is only  $\sim 73 \text{ km s}^{-1}$  redshifted with respect to the systemic redshift of the quasar. The striking feature in Fig. A3 is that the DLA is  $\sim 880 \text{ km s}^{-1}$  blueshifted with respect to the Ly $\alpha$  emission. This is the largest velocity separation seen between the DLA and the narrow Ly $\alpha$  emission line in our sample. This is also the largest separation between the DLA and the quasar. This large velocity offset suggests that

the Ly $\alpha$  emission may be associated with the quasar and not the DLA.

Although SNR is not very high, we note that the flux on the trace derived by our decomposition is smaller along PA = NS compared to PA = EW (see panel (c) of Fig. A4). Actually, the slit width for the two PAs are not the same: 0.8 and 1.0 arcsec for PA = NS and PA = EW, respectively. This is because the seeing was better for PA = NS. We also note that a point-like source is present on the 2D spectrum at PA = EW at the velocity of  $\sim 50 \text{ km s}^{-1}$  relative to the quasar (see panel (a) of Fig. A4). We believe that this point-source is contributing to the flux on the trace. This source is not seen along PA = NS because of the better seeing and smaller slit-width.

If we assume that this point-like source of Ly $\alpha$  emission arises from a star-forming region inside a foreground (or the host) galaxy, we can estimate the star formation rate (SFR) implied by its Ly $\alpha$  luminosity. Integrating over the region where this compact emission is detected, we derive a flux of  $f = 3.26 \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2}$ , with corresponding Ly $\alpha$  luminosity of  $L = 1.40 \times 10^{42} \text{ erg s}^{-1}$ . Assuming the standard case B recombination theory and using the relation proposed by Kennicutt (1998), we get  $\text{SFR} = 1.3 \text{ M}_{\odot} \text{ yr}^{-1}$ . This is a lower limit to the SFR as, in addition to the slit loss, dust extinction and/or absorption by foreground neutral hydrogen could diminish the actual Ly $\alpha$  flux radiated away from the galaxy. Moreover, Erb et al. (2006) showed that, in Lyman break galaxies (LBGs),  $I(\text{Ly}\alpha)/I(\text{H}\alpha) = 0.6$ . Therefore, if our point-like source is an LBG, this implies a higher SFR of  $18.6 \text{ M}_{\odot} \text{ yr}^{-1}$ . The velocity separation of  $\sim 54 \text{ km s}^{-1}$  of this point-like source from the quasar, along with its small impact parameter ( $\sim 0.5 \text{ arcsec}$  or  $\sim 4 \text{ kpc}$ ) suggests that it might be inside the zone-of-influence of the quasar. Therefore, the observed star formation activity might have been triggered by the strong feedback from the AGN. Alternatively, this compact Ly $\alpha$  emission could have been induced by the quasar through the Ly $\alpha$  fluorescence emission (Srianand et al. 2016).

The 2D spectra of this quasar reveal extended Ly $\alpha$  emission along both PAs (Fig. A4). Along PA = NS, the emission is equally extended up to  $\sim 1.8 \text{ arcsec}$  (15.5 kpc) to the north and south directions. A notable feature along PA = EW is that the velocity spread of the emission ( $\sim 500 \text{ km s}^{-1}$ ) is similar along the trace and at  $\sim 1.3 \text{ arcsec}$  (11 kpc) away from the trace to the west. The emission is also spatially more extended to the west, reaching out to  $\sim 2.4 \text{ arcsec}$  (20 kpc). The presence of the point-like source of Ly $\alpha$  emission could in part be responsible for the high velocity extent of the envelope ( $> 500 \text{ km s}^{-1}$ ) towards the west.

The eclipsing DLA along this line of sight is  $\sim 810 \text{ km s}^{-1}$  blueshifted with respect to  $z_{\text{em}}$ . The lack of N V and O VI absorption lines and the low metallicity of the absorber argue against a scenario in which the DLA is associated with outflowing interstellar medium from the quasar host. Alternatively, the absorber may arise from a foreground galaxy unrelated to the quasar.

### 3.4 SDSS J115432.67-021537.9

For this quasar, we detect emission lines from C IV  $\lambda 1548$ , He II  $\lambda 1640$ , Si III]  $\lambda 1892$ , and C III]  $\lambda 1909$ . To estimate the systemic redshift of the quasar, a single Gaussian is fit to



the He II emission line with  $z_{\text{em}} = 2.1810$ . A similar fit to the C III] emission line gives  $z = 2.1830$ . We adopt the former as the systemic redshift of the quasar because the He II line is a more reliable redshift indicator. Panel (a) of Fig. A5 shows the emission lines and their Gaussian fits.

Associated with the eclipsing DLA along this line of sight, we detect metal absorption lines from Si II, Fe II, Al II, Al III, Mg I, Mg II, C IV, Si IV, and possibly N V. The spectral regions corresponding to the O I  $\lambda$ 1302, C II  $\lambda$ 1334, C II\*  $\lambda$ 1335, and N V  $\lambda$ 1339,1402 absorption lines are strongly affected by noise (see panel (c) of Fig. A5). We use four Fe II absorption lines to derive the redshift of the damped Ly $\alpha$  system ( $z_{\text{abs}} = 2.1853$ ). We also tried to constrain the Doppler parameter using some Fe II transitions (see panel (b) of Fig. A5). Following the same approach as in previous sections, one can see that the best  $b$ -value to fit the four Fe II transitions is  $b \sim 20 \text{ km s}^{-1}$ . We adopted this  $b$ -value and subsequently fit the other absorption lines. Panel (c) of Fig. A5 illustrates the observed velocity profiles and VPFIT solutions (where applicable) of different species. The parameters are given in Tables 3 & 4. A damped profile fitted to the Ly $\alpha$  absorption line resulted in  $\log N_{\text{HI}} = 21.75 \pm 0.10$ . The fit is shown as a red curve in panel (d) of Fig. A5 with the two green curves showing the  $\pm 1\sigma$  uncertainty in the H I column density. This DLA is 103 and  $405 \text{ km s}^{-1}$  blueshifted compared to the Ly $\alpha$  emission and systemic redshift of the quasar, respectively (see panel (a) of Fig. A5 and Table 2). The derived metallicity of this absorber is  $[\text{Si}/\text{H}] = -1.71 \pm 0.20$ .

The extended Ly $\alpha$  emission is detected along both PAs, with maximum extension reaching  $\sim 3.2 \text{ arcsec}$  (27 kpc) similarly to the east and south of the quasar as shown in Fig. A6. We checked that the emission seen on the trace in the velocity range  $-500 < v < 0 \text{ km s}^{-1}$  along PA = NS is real. This emission, however, is barely detected along PA = EW, both because the emission is intrinsically faint and the SNR of the spectrum is lower along this PA. Overall, the spectra of the quasar trace for the two PAs are consistent within the errors (see panel (c) of Fig. A6).

As shown in panel (c) of Fig. A6, the Ly $\alpha$  profile on the quasar trace is clearly asymmetric. Here, the Ly $\alpha$  flux sharply rises on the blue side and slowly decreases on the red side of the profile. Note that the blue edge of the profile (marked by a pink arrow) is close to the systemic redshift of the quasar ( $\delta v \sim 60 \text{ km s}^{-1}$ ). Remarkably, we detect a small peak on the blue side of the profile at  $v \sim -300 \text{ km s}^{-1}$ . The presence of this peak could be understood in the context of resonant scattering of Ly $\alpha$  photons. Simulations have shown that Ly $\alpha$  radiation should generally escape the galaxy with a double-peaked profile (Verhamme et al. 2006; Laursen et al. 2009; Noterdaeme et al. 2012) but observations reveal that the blue peak is usually diminished or in some cases completely suppressed (Fynbo et al. 2010). The presence of strong galactic winds, absorption and dust extinction could be responsible for the suppression of the blue peak (Verhamme et al. 2008).

On the other hand, one could also fit a Gaussian function to the Ly $\alpha$  emission seen on the quasar trace. This Gaussian function is shown as a green dotted curve in panel (c) of Fig. A6. One could now reproduce the observed asymmetric Ly $\alpha$  emission profile by putting some Ly $\alpha$  absorption (blue dotted profile in panel (c) of Fig. A6) on top

of the green dotted curve. Note that the blue dotted profile, located at  $v \sim -40 \text{ km s}^{-1}$  relative to the quasar, is  $\sim 150 \text{ km s}^{-1}$  blueshifted with respect to the green dotted curve. This is similar to what is seen in Lyman break galaxies which typically exhibit redshifted emission and blueshifted absorption in Ly $\alpha$  (Shapley et al. 2003). No low-ion is associated with this Ly $\alpha$  absorption while the C IV, Si IV and possibly N V absorption that are seen at  $v \sim -635 \text{ km s}^{-1}$  could probably be partly associated with it.

### 3.5 SDSS J125302.00+100742.3

The quasar has the best SNR spectrum in our sample. Unfortunately, the O I  $\lambda$ 1304 and He II  $\lambda$ 1640 emission lines are not detected and the C III]  $\lambda$ 1909 emission line region is heavily affected by sky emission and telluric absorption lines. However, we could still fit Gaussian functions to the C IV and Si IV emission lines to get  $z = 3.0150$  and  $3.0170$ , respectively. In the analysis of this system, we adopt  $z_{\text{em}} = 3.0150$  as the systemic redshift of the quasar. The emission lines and their Gaussian fits are shown in panel (a) of Fig. A7.

Metal absorption lines from O I, C II, C II\*, Fe II, Si II, Si II\*, Al II, Al III, C IV, and Si IV are detected in the eclipsing DLA along this line of sight (see Fig. A7). A single component fit with  $z_{\text{abs}} = 3.0312$  and  $b = 37.0 \text{ km s}^{-1}$  was conducted on the low-ion species. The redshift and  $b$ -value were determined through a simultaneous fit to the five Si II transitions (i.e. Si II  $\lambda$ 1190,  $\lambda$ 1193,  $\lambda$ 1304,  $\lambda$ 1526, and  $\lambda$ 1808). It can be seen from panel (b) of Fig. A7 that Doppler parameters less than  $37 \text{ km s}^{-1}$  overpredict the observed Si II  $\lambda$ 1808 optical depth. The parameters of the fit to the low and high ion species are reported in Tables 3 & 4. The H I column density of  $\log N_{\text{HI}} = 21.30 \pm 0.10$  was determined by fitting damping profiles on the Ly $\alpha$  and Ly $\beta$  absorption lines, with the redshift fixed to that of the low-ions (see panel (d) of Fig. A7). By fitting the five detected Si II transitions we derive:  $[\text{Si}/\text{H}] = -1.45 \pm 0.20$ . We also tentatively derive  $[\text{C}/\text{H}] = -1.61 \pm 0.20$  and  $[\text{O}/\text{H}] > -1.95$ . From the Fe II  $\lambda$ 1608 absorption we derive  $[\text{Fe}/\text{H}] = -2.53 \pm 0.20$  indicating significant depletion of this element on to dust.

While low-ion absorption profiles are dominated by a single component at  $v = 0 \text{ km s}^{-1}$  ( $z_{\text{abs}} = 3.0312$ ), high-ion species are mainly seen in three distinct components, namely at  $v = 0$ ,  $-200$ , and  $-620 \text{ km s}^{-1}$  (see panel (c) of Fig. A7). Out of these three components, N V and O VI are only seen at  $v = -620$  and  $-200 \text{ km s}^{-1}$ , with no N V associated with the DLA at  $v = 0 \text{ km s}^{-1}$ . Note that N V absorption is the strongest at  $v = -620 \text{ km s}^{-1}$ ; this is also the case for C IV and O VI but not Si IV as it has the weakest absorption at this velocity. This clearly shows that the gas is progressively getting more ionized as we go to higher velocities relative to the DLA. This gas must be located close to the AGN as indicated as well by the presence of Si II\* absorption (see Paper I). It is interesting to note that Ly $\alpha$  emission on the trace is detected over a large velocity range ( $\sim 1500 \text{ km s}^{-1}$ ) which covers all these absorption components.

In addition to the narrow Ly $\alpha$  emission line that is detected in the DLA trough, it seems that its corresponding narrow Ly $\beta$  emission line is also detected in the trough of the damped Ly $\beta$  absorption profile with the flux ratio of  $I(\text{Ly}\alpha)/I(\text{Ly}\beta) < 9.2$ , and the integrated flux of  $f_{\text{Ly}\beta} = (1.8 \pm 0.4) \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2}$  (see Fig. 3).

This ratio is for the strongest component of the Ly $\alpha$  emission seen in the range  $-400 < v < 400 \text{ km s}^{-1}$ . For the whole Ly $\alpha$  emission, extending from  $-1100$  to  $400 \text{ km s}^{-1}$ , this ratio is  $< 14.6$ . Note that for the temperature range of  $100 \leq T_e \leq 20\,000$  this ratio should be in the range  $9.5 \leq I(\text{Ly}\alpha)/I(\text{Ly}\beta) \leq 4.0$  (Martin 1988). Jiang et al. (2016) also reported the possible detection of Ly $\beta$  emission in the Ly $\beta$  absorption trough of a PDLA found towards the quasar SDSS J0952+0114.

As shown in panels (a) and (b) of Fig. A8, the Ly $\alpha$  emission is spatially extended along both PAs. Maximum extension is found to the north reaching out to  $\sim 3.7$  arcsec (30 kpc) from the nucleus emission. The velocity spread of the Ly $\alpha$  emission on the quasar trace is  $\sim 1560 \text{ km s}^{-1}$  which is the largest in our quasar sample (see Table 2 column 8). The kinematic of the extended envelope towards the east and up to a distance of 1.5 arcsec (12 kpc) is remarkably similar to that of the trace (see panel (b) of Fig. A8). The velocity spread of the emission towards the north is  $\sim 500 \text{ km s}^{-1}$  while it is  $\lesssim 300 \text{ km s}^{-1}$  to the south and west direction. Note that the spectrum along the east-west direction has a lower SNR because its exposure time is  $\sim 25\%$  shorter than that of the other PA. However, the emission on the quasar trace for the two PAs are still consistent within the errors (see panel (c) of Fig. A8).

The emission on the quasar trace has two main components at  $100 \lesssim v \lesssim 800$  and  $900 \lesssim v \lesssim 1600 \text{ km s}^{-1}$  (see panel (a) of Fig. A8). The velocity difference between the center of the two components is  $\sim 700 \text{ km s}^{-1}$ . We note that the velocity separation between the DLA and the stronger component of the Ly $\alpha$  emission is  $\sim 30 \text{ km s}^{-1}$ , possibly suggesting they originate in the same region. Note that the velocity separation between the Ly $\alpha$  emission and the quasar itself is not robust as the quasar redshift is derived from the C IV emission line.

## 4 RESULTS AND DISCUSSION

The Ly $\alpha$  emission seen in the trough of the eclipsing DLAs in our sample are all strong and spatially extended along the two observed PAs. The observed properties of the Ly $\alpha$  emission are summarized in Tables 5 and 6. The values in Table 6 are corrected for the Galactic extinction (using the dust map of Schlegel et al. 1998) and the slit loss effect. The slit loss effect was corrected by assuming that the Ly $\alpha$  nebulae are uniform face-on ellipses with major and minor diameters equal to their extent along the two PAs. We then estimated the amount of flux missed by the slit and consequently corrected the observed luminosities.

### 4.1 He II emission line

Since it is possible that the extended Ly $\alpha$  emission seen around quasars might arise from the resonant scattering of Ly $\alpha$  photons from the central AGN, observation of other lines with non-resonant characteristic, like He II  $\lambda 1640$ , is needed to constrain the importance of this effect. If the observed extension of the Ly $\alpha$  envelope results from resonant scattering, then the corresponding He II emission should not be extended. Similarly, detections of spatially extended He II

and Ly $\alpha$  emission on the same scale would imply that resonant scattering of Ly $\alpha$  photons is not important.

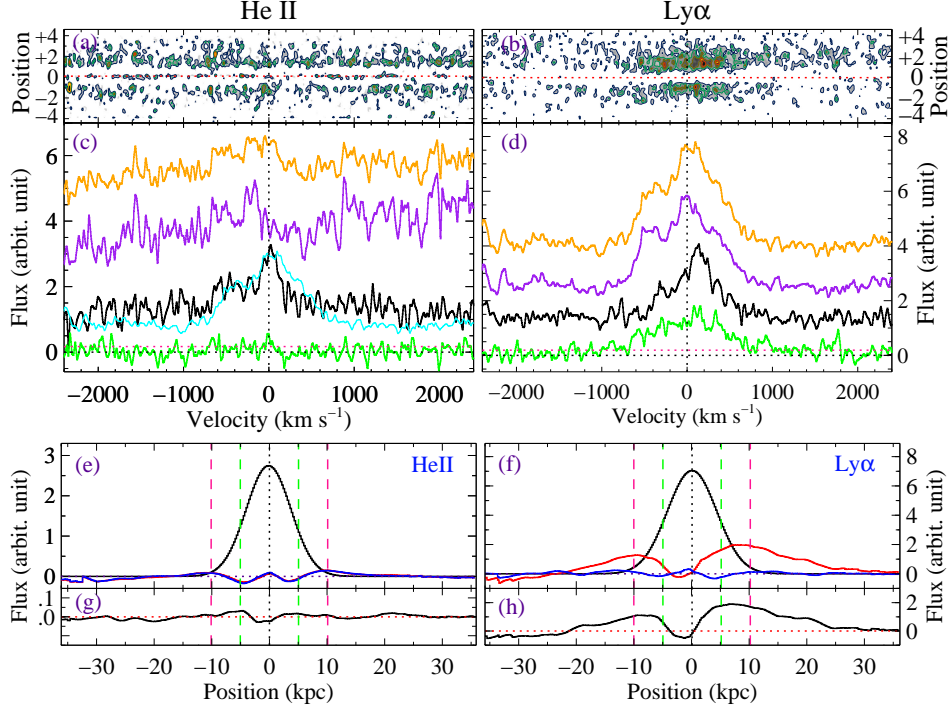
The He II  $\lambda 1640$  emission line is detected in the spectra of three of our quasars (i.e. J0112–0048, J1058+0315 and J1154–0215). The spectra of the remaining quasars (i.e. J0823+0529, J0953+0349, and J1253+1007) also show some weak emission features near the expected position of the He II emission line. However, the low SNR of the latter spectra makes the corresponding detections highly uncertain.

We calculated the integrated flux in the expected extended He II emission line region outside the quasar trace as the sum of the flux in all He II pixels of the 2D spectra corresponding to the detected Ly $\alpha$  extended region. The result is listed in the seventh column of Table 5. We calculated the corresponding  $3\sigma$  detection limit as three times the square root of the sum of the variance of the flux for the same pixels. The result is reported in the eighth column of Table 5. By comparing the values in the seventh and eighth column of Table 5 we can see that no extended He II emission is detected above the  $3\sigma$  detection limit outside the quasar trace in any of our objects.

We also investigate the possible spatial extension of the He II emission by co-adding and comparing the 2D spectra around the position of the He II  $\lambda 1640$  and Ly $\alpha$  emission lines (see Fig. 4). Although Ly $\alpha$  emission is very extended off the quasar trace, its corresponding extended He II emission is apparently not detected in the final stacked spectrum. To quantify this, we integrated the 2D spectra along the spatial direction and compared the result to the background noise level. The result is shown as green curves in panels (c) and (d) of Fig. 4 where the  $1\sigma$  background noise level is marked as horizontal pink dotted lines. Integrating the green curve over the velocity range  $-500 \leq v \leq 500$  results in  $f_{\text{HeII}} = (1.09 \pm 0.89) \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2}$  which is consistent with no detection.

We also integrated the stacked 2D spectra along the spectral direction and the result is shown as red curves in panels (e) and (f) of Fig. 4. For the He II (resp. Ly $\alpha$ ) flux, the integration was performed over the velocity range  $-700 < v < +200 \text{ km s}^{-1}$  (resp.  $-800 < v < +600 \text{ km s}^{-1}$ ). The black curves show the emission in the PSF centered on the trace. The blue curves are the control profiles which are integrated across a wavelength range of the same width as the red lines but  $\sim 100 \text{ \AA}$  away from the He II and Ly $\alpha$  emission lines center. The difference between the red and blue curves is shown in panels (g) and (h) of Fig. 4. The profile in panel (g) is consistent with no He II emission detection outside the quasar trace at the limit of our observations.

All this may imply that the extended Ly $\alpha$  emission seen around these quasars has predominantly resonant-scattering origin, or the ratio of the He II/Ly $\alpha$  emission is much smaller than what is usually seen in quasars, radio galaxies and/or Lyman alpha blobs (Lehnert & Becker 1998; Arrigoni Battaia et al. 2015). If one assumes that the expected He II to Ly $\alpha$  flux ratio is  $\sim 0.1$  which is the typical value observed in Ly $\alpha$  blobs and radio galaxies (Villar-Martín et al. 2007; Prescott et al. 2013; Arrigoni Battaia et al. 2015), then one would expect to detect He II emission at  $\sim 4.5\sigma$  towards the two quasars J0112–0048 (along the EW direction) and J0823+0529 (along both PAs). The expected He II emission flux towards the remaining quasars would still be below the  $3\sigma$  detection limit. The fact that no He II emission is de-



**Figure 4.** *Panels (a) and (b):* Stacked 2D spectra around the He II and Ly $\alpha$  spectral regions after subtracting the emission on the trace. The red dotted horizontal lines mark the center of the trace. The y-axis is position in arcsecond. *Panels (c) and (d):* The green curves show the intensity profiles of the He II and Ly $\alpha$  emission lines integrated over the regions outside the quasar's trace. Actually, the green curves are the 1D profiles of the 2D spectra shown in panels (a) & (b) integrated over the y-axis. The black curves are the stacked 1D spectra of the three quasars (i.e. J0112–0048, J1058+0315, and J1154–0215) for which the He II emission line is detected in the quasar spectrum on the trace. The purple curves are the stacked 1D spectra of the three quasars (i.e. J0823+0529, J0953+0349, and J1253+1007) with uncertain He II detection on the quasar trace. The orange curves are the stacked 1D spectra of all six quasars. For the sake of comparison, the stacked Ly $\alpha$  emission line profile (scaled arbitrarily) is also overplotted as a cyan curve in panel (c). The horizontal pink dotted lines mark the 1 $\sigma$  uncertainty in the flux. The origin of the velocity plots is at  $z = 2.5742$  which is the mean redshift of all six quasars. Note that, for the sake of better illustration, the black, purple, and orange profiles are arbitrarily shifted along the y-axis. *Panels (e) and (f):* the black curve shows the emission in the quasar's PSF centered on the trace, integrated over the spectral width of the He II (resp. Ly $\alpha$ ) emission line. The red curve is the intensity profile of the same region but after subtracting the quasar trace and the blue curve is the control profile. The control profile is integrated across a wavelength range of the same width as the red and black curves but centered 100 Å redder (resp. bluer) than the He II (resp. Ly $\alpha$ ) emission line. Note that the mean flux of the control region outside the quasar trace was subtracted from the green curve in panel (c) to correct for the non-zero residual flux (see the text). The green and pink vertical dashed lines show the FWHM and full width of the quasar PSF, respectively. *Panels (g) and (h):* The black curves show the difference between the red and blue curves in panels (e) & (f).

tected above the 3 $\sigma$  detection limit towards J0112–0048 and J0823+0529 suggests that the He II/Ly $\alpha$  ratio towards these two quasars is below 0.1, and thus argues for resonant scattering of Ly $\alpha$  photons being a dominant process in these quasars.

**Table 5.** Derived parameters of emission lines. First column: slit position angles. Second column: spatial extent of the Ly $\alpha$  emission (i.e. the diameter) of the envelope in both arcsecond and kpc. Third column: flux of the unresolved region which is seen on the quasar trace. Fourth column: flux of the extended Ly $\alpha$  envelope which is seen beyond the quasar trace. Fifth column:  $3\sigma$  detection limit (DL) of the Ly $\alpha$  emission envelope outside the quasar trace. Sixth column:  $1\sigma$  uncertainty in the Ly $\alpha$  surface brightness. Seventh column: integrated flux over the expected He II emission line region outside the quasar trace. Eighth column:  $3\sigma$  detection limit of the He II emission envelope outside the quasar trace. Ninth column:  $3\sigma$  upper limit He II/Ly $\alpha$  ratio determined from the values given in the eighth and fourth columns.

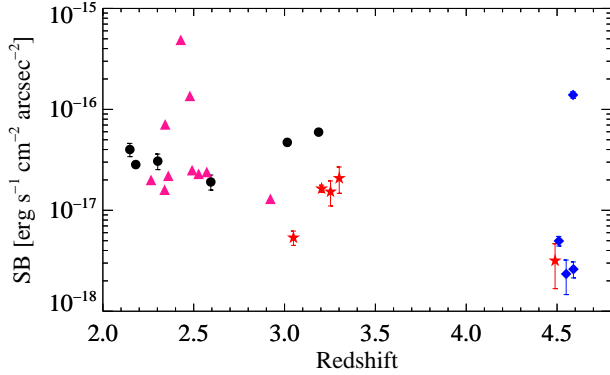
PA	Extent ("; kpc)	NEL flux(Ly $\alpha$ ) [erg s $^{-1}$ cm $^{-2}$ ]	Envlp. flux(Ly $\alpha$ ) [erg s $^{-1}$ cm $^{-2}$ ]	$3\sigma$ DL <sub>Ly<math>\alpha</math></sub> <sup>a</sup> [erg s $^{-1}$ cm $^{-2}$ ]	$1\sigma$ uncertainty <sup>b</sup> [erg s $^{-1}$ cm $^{-2}$ arcsec $^{-2}$ ]	Envlp. flux(HeII) <sup>c</sup> [erg s $^{-1}$ cm $^{-2}$ ]	$3\sigma$ DL <sub>HeII</sub> <sup>c</sup> [erg s $^{-1}$ cm $^{-2}$ ]	Flux ratio (HeII/Ly $\alpha$ )
SDSS J0112+0048								
NS	(5.1; 43)	$2.54(\pm 0.10) \times 10^{-16}$	$1.04(\pm 0.12) \times 10^{-16}$	$4.46 \times 10^{-17}$	$0.92 \times 10^{-17}$	$1.65 \times 10^{-18}$	$2.01 \times 10^{-17}$	$< 0.19$
EW	(4.9; 42)	$2.46(\pm 0.37) \times 10^{-16}$	$2.53(\pm 0.44) \times 10^{-16}$	$1.36 \times 10^{-16}$	$3.55 \times 10^{-17}$	$6.42 \times 10^{-18}$	$1.69 \times 10^{-17}$	$< 0.07$
SDSS J0823+0529								
NS	(5.5; 42)	$3.59(\pm 0.10) \times 10^{-16}$	$3.97(\pm 0.10) \times 10^{-16}$	$4.05 \times 10^{-17}$	$0.74 \times 10^{-17}$	$1.22 \times 10^{-17}$	$2.21 \times 10^{-17}$	$< 0.06$
EW	(6.0; 46)	$3.36(\pm 0.10) \times 10^{-16}$	$2.68(\pm 0.10) \times 10^{-16}$	$4.15 \times 10^{-17}$	$0.92 \times 10^{-17}$	$1.24 \times 10^{-17}$	$2.04 \times 10^{-17}$	$< 0.08$
SDSS J0953+0349								
NS	(3.6; 30)	$1.27(\pm 0.12) \times 10^{-16}$	$0.52(\pm 0.11) \times 10^{-16}$	$4.08 \times 10^{-17}$	$0.93 \times 10^{-17}$	$8.47 \times 10^{-18}$	$3.73 \times 10^{-17}$	$< 0.71$
EW	(3.1; 26)	$1.22(\pm 0.10) \times 10^{-16}$	$0.54(\pm 0.10) \times 10^{-16}$	$3.41 \times 10^{-17}$	$1.15 \times 10^{-17}$	$6.70 \times 10^{-18}$	$3.06 \times 10^{-17}$	$< 0.57$
SDSS J1058+0315								
NS	(3.7; 31)	$0.70(\pm 0.19) \times 10^{-16}$	$0.65(\pm 0.20) \times 10^{-16}$	$4.39 \times 10^{-17}$	$1.59 \times 10^{-17}$	$7.82 \times 10^{-18}$	$1.78 \times 10^{-17}$	$< 0.27$
EW	(4.1; 35)	$1.11(\pm 0.18) \times 10^{-16}$	$1.15(\pm 0.17) \times 10^{-16}$	$5.42 \times 10^{-17}$	$1.80 \times 10^{-17}$	$7.35 \times 10^{-18}$	$2.18 \times 10^{-17}$	$< 0.19$
SDSS J1154+0215								
NS	(6.0; 51)	$1.19(\pm 0.10) \times 10^{-16}$	$1.01(\pm 0.10) \times 10^{-16}$	$3.91 \times 10^{-17}$	$0.53 \times 10^{-17}$	$6.24 \times 10^{-18}$	$2.11 \times 10^{-17}$	$< 0.21$
EW	(5.4; 46)	$1.23(\pm 0.15) \times 10^{-16}$	$1.82(\pm 0.15) \times 10^{-16}$	$4.51 \times 10^{-17}$	$1.03 \times 10^{-17}$	$3.47 \times 10^{-18}$	$2.22 \times 10^{-17}$	$< 0.12$
SDSS J1253+1007								
NS	(6.4; 51)	$2.66(\pm 0.18) \times 10^{-16}$	$2.26(\pm 0.21) \times 10^{-16}$	$5.93 \times 10^{-17}$	$1.32 \times 10^{-17}$	$1.75 \times 10^{-17}$	$4.07 \times 10^{-17}$	$< 0.18$
EW	(4.9; 39)	$2.62(\pm 0.15) \times 10^{-16}$	$2.34(\pm 0.18) \times 10^{-16}$	$6.23 \times 10^{-17}$	$1.77 \times 10^{-17}$	$2.37 \times 10^{-17}$	$4.45 \times 10^{-17}$	$< 0.19$

<sup>a</sup> The  $3\sigma$  detection limit is calculated from the standard deviation (in the flux) of the spectral and spatial pixels over which the Ly $\alpha$  emission outside the quasar trace is detected.

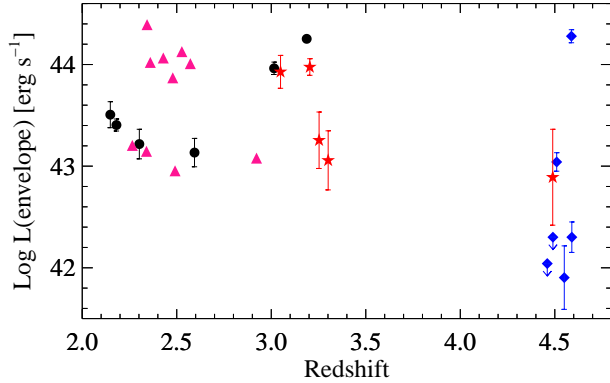
<sup>b</sup> The  $1\sigma$  uncertainty in the flux is used to determine the spatial extent of the Ly $\alpha$  envelope.

<sup>c</sup> Since the He II emission envelopes are apparently not detected outside the quasar trace in all our spectra, the integration is performed over the same spectral and spatial extent as the corresponding Ly $\alpha$  emission envelope.





**Figure 5.** Average surface brightness of the Ly $\alpha$  envelopes as a function of redshift for our sample (black filled circles), together with the CJ06 (red filled stars), NC12 (blue filled squares) and Villar-Martín et al. (2003, pink triangles) objects, all corrected for the redshift dimming effect. The mean redshift of our quasars (i.e.  $z \sim 2.5$ ) is taken as the reference redshift to correct for this effect.

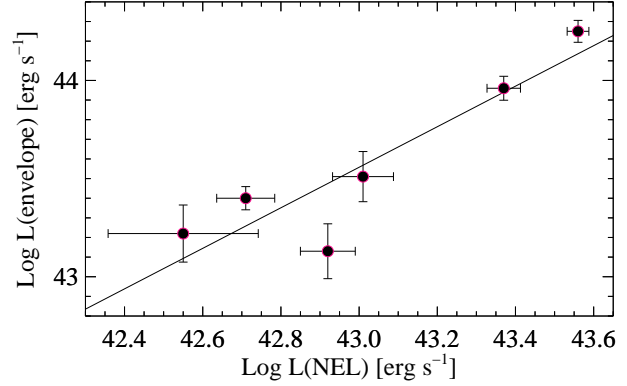


**Figure 6.** Ly $\alpha$  luminosity of the envelopes versus quasar redshift. The symbols represent the same samples as in Fig.5.

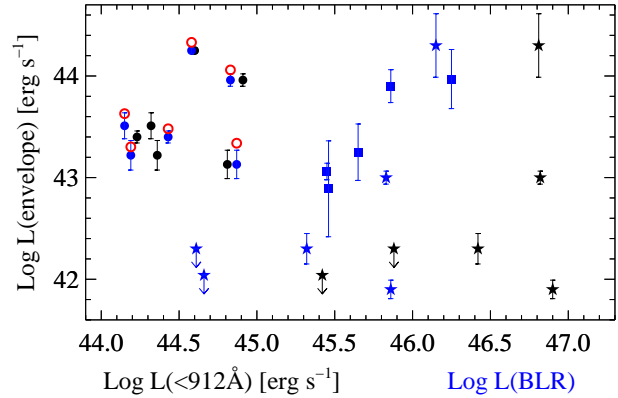
Foltz et al. (1988) and Heckman et al. (1991b) found that the quasar HeII emission flux is  $\sim 30\%$  of that of the Ly $\alpha$  envelope while in our case, it is  $\sim 5\text{--}10\%$ . The discrepancy could in part be due to the uncertain redshift of the Ly $\alpha$  envelope in Heckman et al. (1991a) narrow band images, which led to  $\sim 30\%$  of uncertainty in their Ly $\alpha$  fluxes. The uncertain redshift of the envelope makes it difficult to precisely place the Ly $\alpha$  emission within the band-pass of an interference filter. Moreover, in Heckman et al. (1991a) sample, in contrast to ours, the Ly $\alpha$  emission from the BLR of the quasar is not extinguished by the presence of a strong eclipsing DLA. Therefore, de-convolution of the strong broad Ly $\alpha$  emission could lead to the underestimation of the Ly $\alpha$  flux of the envelope by over-subtracting the emission close to the central region. In our sample, this effect is minimum.

## 4.2 Redshift dependence

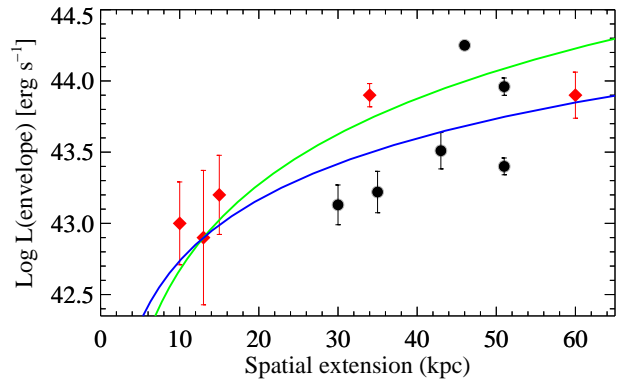
NC12 suggested that quasars at higher redshifts tend to have fainter envelopes. In Fig. 5, we plot the average surface brightness of the Ly $\alpha$  envelopes as a function of redshift for our sample (black filled circles), together with the CJ06 (red



**Figure 7.** Luminosity of the extended Ly $\alpha$  envelopes versus that of the unresolved NEL for our sample. The black line is the fit to all points.



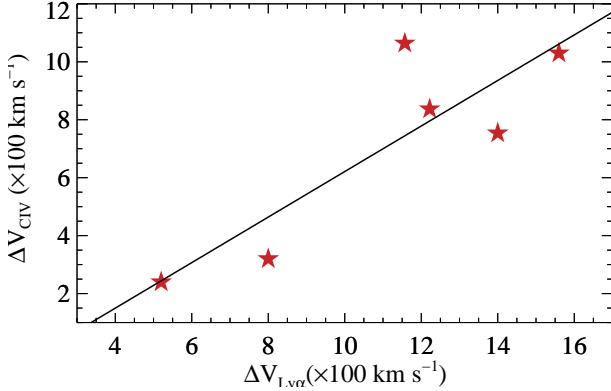
**Figure 8.** Luminosity of the Ly $\alpha$  envelope versus that of the Ly $\alpha$  BLR (blue symbols) and quasar ionizing radiation (black symbols) for the NC12 (stars), CJ06 (squares) and our sample (filled circles). The red circles show the total observed Ly $\alpha$  luminosity as a function of that of the expected Ly $\alpha$  BLR in our sample.



**Figure 9.** Luminosity of the Ly $\alpha$  envelopes as a function of their spatial extension for the CJ06 (red squares) and our sample (black filled circles). The green and blue curves show power law functions with index  $\alpha = 0.5$  and  $0.7$ , respectively (see the text).

**Table 6.** The Ly $\alpha$  flux ( $\text{erg s}^{-1} \text{cm}^{-2}$ ), luminosity ( $\text{erg s}^{-1}$ ) and surface brightness (SB;  $\text{erg s}^{-1} \text{cm}^{-2} \text{arcsec}^{-2}$ ) of the envelopes detected around the quasars in the sample. Note that the flux and luminosity of the extended envelopes are corrected for the Galactic extinction and the slit-clipping effects (see Text). First row: the ID of the quasars in the sample. Second row: The integrated Ly $\alpha$  flux in the quasars’ PSF centered on the trace (i.e. the NEL unresolved luminosity). Third row: the integrated flux in the extended envelopes. Fourth row: the integrated luminosity of the quasars NEL. Fifth row: the luminosity of the extended envelopes. Sixth row: the ionizing luminosity of the quasars, i.e.  $L_{<912}$ . Seventh row: PCA prediction of the Ly $\alpha$  luminosity of the quasars in the BELR (note that this luminosity is measured in the rest-frame wavelength interval 1200–1230 Å). Eighth row: the mean surface brightness of the envelopes.

ID	J0112–0048	J0823+0529	J0953+0349	J1058+0315	J1154–0215	J1253+1007
$f_{\text{NEL}} (\times 10^{-16})$	$2.82 \pm 0.22$	$7.57 \pm 0.20$	$1.43 \pm 0.10$	$0.83 \pm 0.16$	$1.35 \pm 0.10$	$2.80 \pm 0.12$
$f_{\text{envlp}} (\times 10^{-16})$	$8.83 \pm 1.14$	$18.77 \pm 0.50$	$2.35 \pm 0.33$	$3.86 \pm 0.56$	$6.71 \pm 0.41$	$10.88 \pm 0.67$
$L_{\text{NEL}} (\times 10^{43})$	$1.03 \pm 0.10$	$3.61 \pm 0.19$	$0.83 \pm 0.10$	$0.35 \pm 0.10$	$0.51 \pm 0.10$	$2.36 \pm 0.10$
$L_{\text{envlp}} (\times 10^{43})$	$3.21 \pm 0.41$	$17.88 \pm 0.49$	$1.36 \pm 0.19$	$1.65 \pm 0.24$	$2.54 \pm 0.15$	$9.18 \pm 0.56$
$L_{<912} (\times 10^{44})$	2.12	3.98	6.51	2.31	1.71	8.05
$L_{\text{BLR}} (\times 10^{44})$	0.60	6.78	2.69	1.12	2.19	2.75
SB ( $\times 10^{-17}$ )	$4.00 \pm 0.50$	$5.95 \pm 0.16$	$1.91 \pm 0.27$	$3.07 \pm 0.45$	$2.84 \pm 0.17$	$4.71 \pm 0.29$



**Figure 10.** Relation between the velocity extent of the Ly $\alpha$  emission and that of the C IV absorption profile in our sample. The black line is a fit to all data points.

filled stars), NC12 (blue filled squares) and Villar-Martín et al. (2003, pink triangles) objects, all corrected for redshift dimming effect. The envelopes in our sample are  $\gtrsim 10$  times brighter than those at redshift  $z \sim 4$ . The surface brightness seems to steadily decrease with redshift.

Figure 6 presents the luminosity of the Ly $\alpha$  envelopes versus redshift. The symbols are the same as in Fig. 5. The luminosity of the Ly $\alpha$  envelopes in our sample are almost the same as those in Villar-Martín et al. (2003) and CJ06. Our brightest envelope has the same total luminosity as the brightest object in NC12 while their faintest object is  $\sim 17$  times less luminous than our faintest one.

NC12 argued that their lower surface brightness may be due to the deeper sensitivity of their observation which led to the more extended envelopes compared to those of CJ06. The mean size of the envelopes in the NC12, CJ06 and our sample are 45, 26.4 and 41 kpc, respectively. The mean detection limit of the NC12 observations is  $\sim 2.5 \times 10^{-17} \text{ erg s}^{-1} \text{cm}^{-2}$  (after taking into account the redshift dimming effect) while in our case it is  $\sim 4.7 \times 10^{-17} \text{ erg s}^{-1} \text{cm}^{-2}$ . This indicates that the large extent and higher surface brightness of our envelopes cannot be attributed to the depth of the observation. Our envelopes, despite having less depth, still are almost as extended as the NC12’s envelopes. This further strengthens the idea put

forth by NC12 that higher redshift envelopes may intrinsically be fainter than their lower redshift descendants.

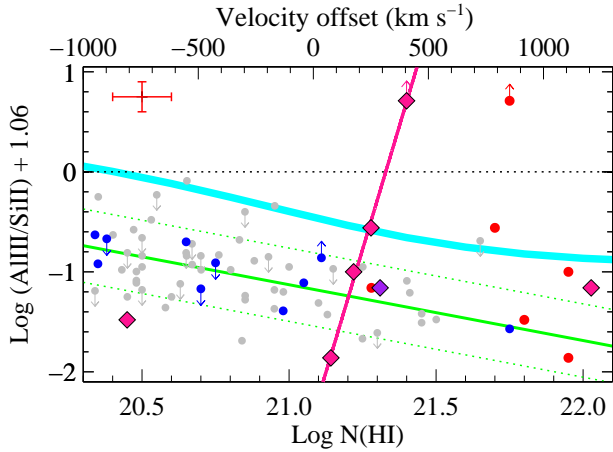
We also checked for any correlation between the surface brightness of the envelope and the velocity width of the Ly $\alpha$  emission line in our sample, and found a mild correlation between them. The correlation coefficient is 0.64 implying a 17% probability of finding this trend by chance occurrence. If we take into account the NC12 and CJ06 samples, then the correlation disappears, suggesting that the trend found in our sample may not be real. However, the number of quasars is not large enough to be statistically significant. Observation of a large sample of quasars with extended Ly $\alpha$  envelope may help us settle this question.

### 4.3 Quasar narrow Ly $\alpha$ emission

If the narrow Ly $\alpha$  emission on the spectrum trace is associated with the unresolved inner part of the extended Ly $\alpha$  envelope as suggested by Heckman et al. (1991b) then one would expect a correlation between the Ly $\alpha$  luminosity on the trace and in the extended region. Since the narrow Ly $\alpha$  emission line in a quasar spectrum is usually strongly blended and contaminated by the emission from the BLR, no attempt has ever been made to correlate its luminosity with that of the extended envelope. For the first time, in this work we can directly examine this correlation for the objects in our sample. Figure 7 presents the luminosity of the extended Ly $\alpha$  envelopes as a function of the luminosity of the Ly $\alpha$  emission seen on the quasar trace for the objects in our sample. A strong correlation with a coefficient of 0.90 is found between the two luminosities. This correlation implies that much of the narrow spatially unresolved Ly $\alpha$  emission seen on the quasar trace is probably associated with the inner part of the extended Ly $\alpha$  envelope. This correlation can be interpreted as a consequence of the direct influence of the quasars on their Ly $\alpha$  envelopes.

### 4.4 Quasar vs. the envelope luminosities

We investigate the possible correlation between the broad Ly $\alpha$  line luminosity of the quasars and that of the extended Ly $\alpha$  envelopes. Since the broad Ly $\alpha$  emission line is fully extinguished in our spectra, its luminosity is calculated from



**Figure 11.** The Al III/Si II ratio as a function of  $N(\text{H I})$  for the Berg et al. (2015, grey points), EP10 (blue points), and our eclipsing DLAs (red points). The red error bar on the upper left side of the plot shows the uncertainty in the column densities of our data points. The green solid line is the fit to the Berg et al. (2015) DLAs. The two green dotted lines show the standard deviation of the grey points. The thick cyan line shows the result of a grid of CLOUDY models constructed for the ionization parameter  $\log U = 0.0$ , a nominal hydrogen density  $\log n_{\text{H I}} = 1.0$ , and hydrogen column density in the range  $20.30 \leq \log N(\text{H I}) \leq 22.10$ . The pink diamonds show the Al III/Si II ratios in our sample as a function of the velocity offset between the DLAs and their background quasars (upper x-axis scale where positive values indicate a redshift i.e. the DLA falling towards the quasars). The pink line shows the fit to the data points with positive velocity offsets, after excluding the point at  $\log N(\text{H I}) < 21.5$  corresponding to J1253+1007. The purple diamond shows the value for the DLA towards J1253+1007, after correcting the quasar redshift for systemic shift (see the text).

the principle component analysis (PCA) reconstruction of this line (Pâris et al. 2011, 2014). To be consistent with previous work, we integrate the 1D quasar spectra in the rest-frame wavelength interval of 1200–1230 Å and then measure the luminosity. The result is shown in Fig. 8 as blue symbols. The correlation coefficient for the data points in the CJ06 (blue squares), NC12 (blue stars), our quasars (blue filled circles) and for the combination of the three samples are 0.92, 0.61, 0.24 and 0.11, respectively. The lack of a correlation in the combined sample mainly stems from the absence of a correlation in our sample. We added the luminosity of the unresolved NEL to that of the extended envelope in our sample (the result is shown as red open circles in Fig. 8), and still found no correlation with the Ly $\alpha$  BLR luminosity.

We also investigated whether the extended Ly $\alpha$  envelope luminosities are correlated with the ionizing radiation flux from the quasars. We used the same technique described in paper I to estimate the ionizing flux of the quasars in our sample. The result is shown as black symbols in Fig. 8. We found correlation coefficients of 0.20, 0.32 and  $-0.41$  for the objects in the NC12, our sample and the total sample, respectively. The lack of a strong correlation between the quasar luminosity and that of its envelope may suggest that processes other than direct photo-ionization are at play such as variations of covering factors and/or dust extinction from one line-of-sight to the other.

#### 4.5 Spatial and velocity extent of the nebulae

The mean sizes (i.e. diameter) of the envelopes in the NC12, CJ06 and our sample are 45, 26 and 41 kpc, respectively. The depth of the observation in our sample is very similar to that of the CJ06 while the NC12 observations are the deepest. This suggests that our envelopes could be more extended if our observations were as deep as the NC12 ones.

The Ly $\alpha$  envelopes around our quasars exhibit two-sided emissions along both PAs. This is in contrast to the CJ06 sample of RQQs in which only one-sided emission is detected. Although one-sided and two-sided envelopes are both reported around RQQs (e.g. Møller et al. 2000 and Weidinger et al. 2005), RLQs are usually observed to have asymmetric two-sided nebulae (Heckman et al. 1991a). Our envelopes, therefore, seem to morphologically resemble those found around RLQs. Figure 9 presents the luminosity of the Ly $\alpha$  envelopes as a function of their spatial extension for the CJ06 (red diamonds) and our sample (black filled circles). A strong correlation with a high probability of  $\sim 99.6\%$  is found between the Ly $\alpha$  luminosity of the extended envelope and its spatial extension for the full sample. This strong correlation confirms the result by CJ06 that more luminous envelopes are also spatially more extended.

Kaspi et al. (2000; 2005) found a relation between the luminosity of the AGN and the size of the BLR,  $R_{\text{BLR}} \sim L^\alpha$  (also see Bentz et al. 2013). Their best value of  $\alpha$  is in the range  $0.5 < \alpha < 0.7$  which is consistent with simple photo-ionization expectations. Interestingly, similar relation seems to be present between the size of the extended Ly $\alpha$  envelope and its luminosity. In Fig. 9, the green and blue curves show the power law functions for  $\alpha = 0.5$  and  $0.7$ , respectively. This could imply that the Ly $\alpha$  envelopes may be strongly affected by the ionizing radiation emanating from the central AGN. The scatter seen in our observed data points around this mean power law relation may result from the non-uniform conditions in the emission regions. Part of this scatter could also be due to the presence of dust in these regions.

In paper I, we suggested that the high ionization gas seen towards J0823+0529 may arise from some warm absorber driven by the accretion disk luminosity. The outflowing material is then stopped by collision with the ISM of the host galaxy, producing shock waves. The shocked material then gets cooled and mixed with the ISM. The outflowing material could also affect the kinematics of the ISM gas. If true, then one would expect a correlation between the kinematics of the ISM gas and that of the outflowing material. In Fig. 10, we plot the relation between the total velocity extension of the Ly $\alpha$  emission and that of the C IV absorption profile reported in Table 2. A correlation coefficient of 0.86 is found in this sample. This correlation may hint at the possibility that the Ly $\alpha$  emission envelopes around the quasars in our sample may be affected by the outflowing material originated from the innermost region of the AGN. However, observation of more quasars with extended Ly $\alpha$  emission are needed to confirm whether this correlation is real.

#### 4.6 Physical properties of the eclipsing DLAs

The first systematic study of the physical properties of PDLAs was done by Ellison et al. (2010, hereafter EP10; also see Ellison et al. 2002). They studied in detail, a sample of 16 PDLAs with a velocity separation  $\delta V < 3000 \text{ km s}^{-1}$  from the quasars. They compared the properties of their PDLAs with those of a control sample of intervening DLAs to investigate the differences between the two populations. Their control sample contains intervening DLAs with  $\delta V > 10000 \text{ km s}^{-1}$  from the Berg et al. (2015b) catalog. In this section, we compare our DLAs with those of EP10 and the control sample.

The velocity offset between the quasars and the eclipsing DLAs in our sample is in the range  $-809 \lesssim \delta V \lesssim 1207 \text{ km s}^{-1}$  (see Table 2 column 5). 5 out of 6 DLAs have positive velocity offset (i.e. DLAs falling towards the quasars) while in the EP10 sample it is 4 out of 16. It is interesting to note that the only object with a negative velocity offset in our sample (i.e. J1058+0315) has also the smallest Ly $\alpha$  velocity extent ( $\Delta V_{Ly\alpha} \sim 520 \text{ km s}^{-1}$ ) and the simplest C IV absorption feature with only one single component. Moreover, the maximum velocity offset of  $\sim 882 \text{ km s}^{-1}$  between the DLA and the extended Ly $\alpha$  emission in our sample is also seen along this line of sight.

##### 4.6.1 Ionization properties

In our eclipsing DLAs we detect high ionization species which in many cases extend hundreds of  $\text{km s}^{-1}$  to the blue of the main low-ion component. C IV and Si IV absorption are detected in all of our eclipsing DLAs. The O VI region in most of our spectra suffers from low SNR and contamination with Ly $\alpha$  forest absorption. Nonetheless, the O VI doublet is detected in the relatively high SNR spectrum of the quasar J1253+1007 in the velocity range  $-850 \lesssim \delta V \lesssim -100 \text{ km s}^{-1}$  (see Fig. A7). Although the O VI  $\lambda 1037$  absorption seems to be slightly blended with some Ly $\alpha$  forest absorption, the similarity between the O VI  $\lambda 1031$  and the N V doublet absorption confirms the detection. At zero velocity, we have one detection (towards J0823+0529) and one strict upper limit (towards J1253+1007) of N V, with no confident N V detection towards the remaining objects. Offset N V and Si IV absorption are seen to the blue at  $v \lesssim -100 \text{ km s}^{-1}$  towards J0953+0349, J1154–0215, and J1253+1007. Moreover, offset C IV absorption is also seen at  $v \lesssim -100 \text{ km s}^{-1}$  towards all our objects except J1058+0315. EP10 found no low-ions associated with their offset high ions while in our case, some strong low-ion transitions (e.g. O I, C II, C II\*) are seen towards J0953+0349 at  $v \sim -660 \text{ km s}^{-1}$ .

In J0953+0349, the velocity separation between the quasar and the two low-ion components are  $-484$  and  $175 \text{ km s}^{-1}$  (see panel (a) in Fig. A1). This is reminiscent of the PDLA studied by Rix et al. (2007) towards the quasar Q2343–BX415. They found two low-ion components, one redshifted by  $\sim 400 \text{ km s}^{-1}$  and the other blueshifted by  $\sim 170 \text{ km s}^{-1}$  relative to the quasar systemic redshift (see their figure 5). They concluded that the presence of prominent high ionization lines in the redshifted component along with the partial coverage of the continuum source (Ofengeim et al. 2015; Klimentenko et al. 2015) are indicative of gas falling

onto the central AGN; and the blueshifted component may be part of the outflowing material of the quasar host galaxy.

The column density ratio  $N(\text{Al III})/N(\text{Al II})$  can be used to study the ionization properties of DLAs. Vladilo et al. (2001) showed that, in the presence of a soft stellar-type ionizing radiation, this ratio decreases when  $N(\text{H I})$  increases. Figure 11 shows Al III/Si II ratios (after correcting for the solar value of Al/Si) as a function of  $N(\text{H I})$  for the Berg et al. (2015, grey points), EP10 (blue points), and our DLAs (red points). In this figure, Si II is used as a proxy for Al II which is mostly saturated in DLAs. EP10 found no apparent difference between the intervening DLAs and their PDLAs. In Fig. 11, the green solid line, which clearly shows the anti-correlation with  $N(\text{H I})$ , is the fit to the Berg et al. (2015) DLAs. The two green dotted lines mark the  $1\sigma$  uncertainty in the Al III/Si II ratios, calculated from the standard deviation of the grey data points in Fig. 11. Interestingly, three of our eclipsing DLAs seem to follow this anti-correlation, implying that the DLA gas is photoionized by a soft radiation and/or if it is close to the AGN, the ionization parameter is very low (Howk & Sembach 1999). The remaining three eclipsing DLAs indicate rather elevated Al III/Si II ratios, with one DLA (towards J1154–0215) having the highest Al III/Si II ratio ( $\gtrsim +0.71$ ) ever reported for a DLA or PDLA.

In Fig. 11, the thick cyan line shows the result of a grid of CLOUDY models constructed for the ionization parameter  $\log U = 0.0$  and a nominal hydrogen density  $\log n_{\text{H I}} = 1.0$ . The combination of the mean AGN spectrum of Mathews & Ferland (1987), the cosmic microwave background (CMB) radiation at  $z = 2.5742$  (mean redshift of all our eclipsing DLAs), and the Haardt-Madau extragalactic spectrum (Haardt & Madau 1996) at the same redshift is taken as the incident radiation hitting the cloud. Note that the mean metallicity  $<[\text{Si}/\text{H}]> = -1.2$  is assumed although the result is not very sensitive to the choice of the metallicity and redshift. As shown in Fig. 11, two of our eclipsing DLAs seem to have Al III/Si II ratios consistent with this CLOUDY model.

As mentioned above, the Al III/Si II ratio in the eclipsing DLA towards J1154–0215 is  $\gtrsim +0.71$  which is  $\sim 6$  times more than the highest value in the Berg et al. (2015) DLA sample (see Fig. 11). We note that this value can even be considered as a *strict* lower limit because the Si II (resp. Al III) column density can be considered as a *strict* upper limit (resp. lower limit; see below and Fig. A5). To get the Si II column density, a Voigt profile fit was conducted on the Si II  $\lambda 1808$  and  $\lambda 1526$  absorption lines. Since the former transition is weak and the latter one is slightly blended to the red, the derived  $N(\text{Si II})$  is taken as an upper limit. On the other hand, the Al III absorption profiles are most probably saturated as the two components seem to have almost the same optical depth. The high value of Al III/Si II ratio towards J1154–0215 could be explained if one assumes a two- or multi-phase medium.

In Fig. 11, the pink diamonds show the Al III/Si II ratios in our sample as a function of the velocity offset between the DLAs and their quasars. In this figure, the upper x-axis represents the velocity offsets in  $\text{km s}^{-1}$ , and positive values indicate a redshift (i.e. the DLAs falling towards the quasar). Taken at face value, there appears to be a strong correlation (with the coefficient of 0.99) between the velocity offsets and the Al III/Si II ratios among the DLAs with positive veloc-



ity offset. The only exception to this is the DLA towards J1253+1007 which exhibits a high positive velocity offset of  $\sim 1207 \text{ km s}^{-1}$ , and apparently does not follow this trend. We note that the redshift of this quasar was obtained by fitting its C IV emission line (see Fig. A7). So, if we apply the known systematic shift of C IV emission line (as reported in Shen et al. 2007) to correct the redshift, we get a velocity offset of  $\sim 290 \text{ km s}^{-1}$  (instead of  $\sim 1207 \text{ km s}^{-1}$ ) between the DLA and the quasar. This new value, which is now more consistent with the correlation mentioned above, is shown as a purple square in Fig. 11. Note that the pink line shows the fit to the data points of DLAs with positive velocity offset, after excluding the one towards J1253+1007. It could be possible that eclipsing DLAs with positive velocity offset are chemically distinct from those with negative velocity offset. The DLA towards J1058+0315 with negative velocity offset of  $-809 \text{ km s}^{-1}$  is probably an intervening gas.

This correlation strongly suggests that DLAs with higher velocity towards the quasars have also higher ionization and therefore may be closer to the AGN which is consistent with the fact that they could be part of an infall flow onto the host galaxy.

#### 4.6.2 The size of the eclipsing DLAs

Since extended Ly $\alpha$  emission is detected in the trough of our eclipsing DLAs, this indicates that the size of the absorbing cloud should be smaller than that of the Ly $\alpha$  emitting central unresolved region. In paper I, we studied in detail the eclipsing DLA seen towards the quasar J0823+0529, which also exhibits some indications of partial coverage of the BELR. We used the CLOUDY photo-ionization code to model the absorber including the Si II\* absorption and derived hydrogen density in the range  $180 < n_{\text{H}} < 710 \text{ cm}^{-3}$ , resulting in the cloud size in the range  $2.3 < l(\text{H I}) < 9.1 \text{ pc}$ .

Si II\* absorption is also detected in the eclipsing DLA towards quasar J1253+1007 (see Fig. A7). Following the same approach as in paper I, we get  $n_{\text{H}} \sim 13 \text{ cm}^{-3}$  and  $l(\text{H I}) \sim 50 \text{ pc}$ . Unfortunately, in the other 4 objects in our sample, the Si II\* absorption is not detected.

Assuming, as in e.g. Prochaska and Hennawi (2009) that the optically thick eclipsing DLAs in our sample have  $n_{\text{H}} > 10 \text{ cm}^{-3}$ , we can derive an indicative upper limit on their size (i.e.  $l \sim N_{\text{HI}}/n_{\text{H}}$ ). The result is given in the last column of Table 2 where the values are in pc. As shown in this table, all our eclipsing DLAs appear to have sizes smaller than 300 pc. Since NELRs in quasars have dimensions of several hundreds of parsecs, our upper limits on the size of the eclipsing DLAs are consistent with the argument that the clouds are smaller than the central unresolved emission region.

## 5 SUMMARY AND CONCLUSIONS

We present spectroscopic observations of six high redshift ( $z_{\text{em}} > 2$ ) quasars, which have been selected because of the presence of a strong proximate ( $z_{\text{abs}} \sim z_{\text{em}}$ ) coronagraphic DLA which covers only the broad line region of the quasar, thus revealing emission from the host galaxy. We detect spatially extended Ly $\alpha$  emission envelopes around the six quasars, with projected spatial extent in the range

$26 \leq d_{\text{Ly}\alpha} \leq 51 \text{ kpc}$ . No correlation is found between the quasar ionizing luminosity and the Ly $\alpha$  luminosity of their extended envelopes. This could be related to the limited covering factor of the extended gas and/or due to the AGN being obscured in other directions than towards the observer. Indeed, we find a strong correlation between the luminosity of the envelope and its spatial extent, which suggests that the envelopes are probably ionized by the AGN. The metallicity of the coronagraphic DLAs is low and varies in the range  $-1.75 < [\text{Si}/\text{H}] < -0.63$ . Highly ionized gas is observed associated with most of these DLAs, probably indicating ionization by the central AGN. One of these DLAs has the highest Al III/Si II ratio ever reported for any intervening and/or proximate DLA. Most of these DLAs are redshifted with respect to the quasar, implying that they might represent infalling gas probably accreted onto the quasar host galaxies through filaments.

### 5.1 Nature of the emitting gas

The main mechanisms proposed to power the extended Ly $\alpha$  emission envelopes around high redshift quasars are photo-ionization by the AGN, and cold accretion of neutral hydrogen gas into the quasar dark matter halo. If ionizing photons from the AGN are responsible for powering the extended Ly $\alpha$  emission, a correlation between the quasar and its envelope luminosity is expected. On the other hand, in the cold accretion scenario, no such correlation is expected.

CJ06 found no correlation between the quasar ionizing luminosity and the luminosity of the Ly $\alpha$  envelope. They argued that the lack of correlation cannot be due to extinction by dust or absorption by neutral hydrogen in the quasar environments which could potentially affect the quasar luminosity at 912 Å. Similarly, NC12 found no correlation between the two luminosities for their full sample, apparently confirming the CJ06 result, but at higher redshifts and for a larger luminosity range. NC12 argued that removing the object BR 2237–0607 from their sample would restore the correlation, implying that the quasar might be the main powering source of the Ly $\alpha$  envelope. But the lack of a correlation for their full sample seems to favor the cold accretion scenario.

In our sample, the quasar ionizing luminosity does not seem to correlate with the extended Ly $\alpha$  envelope luminosity. This is consistent with what is seen in CJ06 and NC12 full samples. However, in section 4.5, we found a strong correlation between the luminosity of the Ly $\alpha$  envelope and its spatial extension. We suggested that this correlation could imply that the quasar ionizing flux might be powering the Ly $\alpha$  envelopes. This seems to be at odds with the apparent lack of a correlation between the quasar ionizing luminosity and the Ly $\alpha$  envelope luminosity. It is possible that the level of extinction by dust significantly varies from one object to the other in our sample, resulting in highly uncertain measurement of the intrinsic quasar luminosities at 912 Å. Moreover, in contrast to the CJ06 and NC12 samples, the presence of the strong eclipsing DLAs at the quasar emission redshift in our sample would also mean higher absorption of the quasar flux by the surrounding neutral hydrogen. These effects could in principle remove the possible correlation that might have existed between the luminosity of the quasar at 912 Å and that of the Ly $\alpha$  envelope in our sample. To cir-

cumvent this problem, one can use the infrared spectra of the quasars to better calibrate the quasar template spectrum and consequently get a better estimate of the quasar luminosity at 912 Å. Better estimate of the quasars ionizing luminosities might restore the correlation.

## 5.2 Nature of the eclipsing DLAs

An important question regarding the origin of the proximate DLAs is whether they are due to outflowing material intrinsic to the quasar or some (infalling) material unrelated to the AGN environment but coincident in redshift with the background quasar. If the DLA is part of some low density ( $n_{\text{H}} < 10 \text{ cm}^{-3}$ ) infalling material close to the central AGN, the quasar's ionizing photons could ionize and photoevaporate it (Prochaska & Hennawi 2009). Although infalling gas is usually expected to have lower metallicity, associated outflowing absorbers tend to have solar or super solar metallicities (Petitjean et al. 1994). This would in principle allow one to distinguish whether the gas is associated or intervening.

EP10 found that their PDLAs with higher H I column densities have metallicities  $\sim 3$  times higher than what is seen for the intervening DLAs, but still below those expected for an associated absorber. They argued that their PDLAs are probably neither associated nor intervening. They suggested that PDLAs probably probe overdense regions in massive galaxies with higher metallicities in dense clusters.

The metallicities of our eclipsing DLAs are low and similar to what is seen in intervening DLAs. This would imply that these absorbers might not be outflowing material driven by the central AGN. The fact that most of our eclipsing DLAs have redshifts larger than that of their background quasars further strengthens the idea that these DLAs could be associated with some less enriched infalling material accreting onto the quasar host galaxies, probably through filaments as was concluded for the quasar J0823+0529 (Fathivavsari et al. 2015).

## ACKNOWLEDGMENTS

We would like to thank the anonymous referee for his/her constructive comments, which helped us to improve the paper. We also thank George Becker for advices on MagE data reduction. We also thank Hadi Rahmani for useful discussion. HFV was supported by the Agence Nationale pour la Recherche under program ANR-10-BLAN-0510-01-02. SL has been supported by FONDECYT grant number 1140838 and partially by PFB-06 CATA.

## REFERENCES

Adelberger, K. L., Shapley, A. E., Steidel, C. C., Pettini, M., Erb, D. K., Reddy, N. A., 2005, *ApJ*, 629, 636  
 Arrigoni Battaia, F., Yang, Y., Hennawi, J. F., Prochaska, J. X., Matsuda, Y., Yamada, T., Hayashino, T., 2015, *ApJ*, 804, 26  
 Arrigoni Battaia, F., Hennawi, J. F., Cantalupo, S., Prochaska, J. X., preprint (arXiv:1604.02942)  
 Asplund, M., Grevesse, N., Sauval, A. J., Scott, P., 2009, *ARA&A*, 47, 481  
 Bahcall, J. N., Spitzer, L. J., 1969, *ApJ*, 156, 63  
 Bentz, M. C. et al., 2013, *ApJ*, 767, 149

Berg, T. A. M., Ellison, S. L., Prochaska, J. X., Venn, K. A., Dessauges-Zavadsky, M., 2015, *MNRAS*, 452, 4326  
 Bergeron, J., Petitjean, P., Cristiani, S., Arnouts, S., Bresolin, F., Fasano, G., 1999, *A&A*, 343, 40  
 Bergeron, J., et al., 2004, *The Messenger*, 118, 40  
 Bordoloi, R., Rigby, J. R., Tumlinson, J., Bayliss, M. B., Sharon, K., Gladders, M. G., Wuyts, E., 2016, *MNRAS*, 458, 1891  
 Borisova, E., Cantalupo, S., Lilly, S. J. et al., preprint (arXiv:1605.01422)  
 Bouché, N., Cresci, G., Davies, R., Eisenhauer, F. et al., 2007, *ApJ*, 671, 303  
 Cantalupo, S., Arrigoni-Battaia, F., Prochaska, J. X., Hennawi, J. F., Madau, P., 2014, *Nature*, 506, 63  
 Christensen, L., Jahnke, K., Wisotzki, L., Sánchez, S. F., 2006, *A&A*, 459, 717  
 Courbin, F., North, P., Eigenbrod, A., Chelouche, D., 2008, *A&A*, 488, 91  
 Croft, R. A. C., Hernquist, L., Springel, V., Westover, M., White, M., 2002, *ApJ*, 580, 634  
 Croft, R. A. C., 2004, *ApJ*, 610, 642  
 Churchill, C. W., Trujillo-Gomez, S., Nielsen, N. M., Kacprzak, G. G., 2013, *ApJ*, 779, 87  
 Dawson, K. S. et al., 2013, *AJ*, 145, 10  
 Dijkstra, M., Loeb, A., 2009, *MNRAS*, 400, 1109  
 D'Odorico, V., Petitjean, P., Cristiani, S., 2002, *A&A*, 390, 13  
 D'Odorico, V., et al., 2013, *MNRAS*, 435, 1198  
 Ellison, S. L., Yan, L., Hook, I. M., Pettini, M., Wall, J. V., Shaver, P., 2002, *A&A*, 383, 91  
 Ellison, S. L., Prochaska, J. X., Hennawi, J., Lopez, S., Usher, C. Wolfe, A. M., Russell, D. M., Benn, C. R., 2010, *MNRAS*, 406, 1435  
 Ellison, S. L., Prochaska, J. X., Mendel, J. T., 2011, *MNRAS*, 412, 448  
 Erb, D. K., Steidel, C. C., Shapley, A. E., Pettini, M., Reddy, N. A., Adelberger, K. L., 2006, *ApJ*, 647, 128  
 Fardal, M. A., Katz, N., Gardner, J. P., Hernquist, L., Weinberg, D. H., Davé, R., 2001, *ApJ*, 562, 605  
 Fathivavsari, H., Petitjean, P., Ledoux, C., Noterdaeme, P., Srianand, R., Rahmani, H., Ajabshirizadeh, A., 2013, *MNRAS*, 435, 1727  
 Fathivavsari, H., Petitjean, P., Noterdaeme, P., Pâris, I., Finley, H., López, S., Srianand, R., Sánchez, P., 2015, *MNRAS*, 454, 876  
 Finley, H. et al., 2013, *A&A*, 558, 111  
 Foltz, C. B., Chaffee, F. H. Jr., Weyman, R. J., Anderson, S. F., 1988. In *QSO Absorption lines: Probing the Universe: Proceedings of the QSO Absorption line meeting*, Baltimore, MD, May 19-21, 1987. Cambridge and New York, Cambridge University Press, pp53-65  
 Fried, J. W., 1998, *A&A*, 331, 73  
 Fynbo, J. U., Burud, I., Møller, P., 2000, *A&A*, 358, 88  
 Fynbo, J. P. U. et al., 2010, *MNRAS*, 408, 2128  
 Haiman, Z., Spaans, M., Quataert, E., 2000, *ApJ*, 537, 5  
 Haiman, Z., Rees, M. J., 2001, *ApJ*, 556, 87  
 Heckman, T. M., Miley, G. K., Lehnert, M. D., van Breugel, W., 1991a, *ApJ*, 370, 78  
 Heckman, T. M., Lehnert, M. D., Miley, G. K., van Breugel, W., 1991b, *ApJ*, 381, 373  
 Hennawi, J. F., Prochaska, J. X., Kollmeier, J., Zheng, Z., 2009, *ApJ*, 693, 49  
 Hennawi, J. F., et al., 2006, *ApJ*, 651, 61  
 Hennawi, J. F., Prochaska, J. X., 2007, *ApJ*, 655, 735  
 Hennawi, J. F., Prochaska, J. X., Cantalupo, S., Arrigoni-Battaia, F., 2015, *Science*, 348, 779  
 Hewett, P. C., Wild, V., 2010, *MNRAS*, 405, 2302  
 Howk, J. C., Sembach, K. R., 1999, *ApJ*, 523, 141  
 Hu, E. M., Cowie, L. L., 1987, *ApJ*, 317, 7  
 Jiang, P., Zhou, H., Pan, X. et al., 2016, *ApJ*, 821, 1

Kaspi, S., Smith, P. S., Netzer, H., Maoz, D., Jannuzi, B. T., Giveon, U., 2000, *ApJ*, 533, 631

Kaspi, S., Maoz, D., Netzer, H., Peterson, B. M., Vestergaard, M., Jannuzi, B. T., 2005, *ApJ*, 629, 61

Kelson, D. D., 2003, *PASP*, 115, 688

Kennicutt, R. C., Jr., 1998, *ARA&A*, 36, 189

Klimenko, V. V., Balashev, S. A., Ivanchik, A. V., Ledoux, C., Noterdaeme, P., Petitjean, P., Srianand, R., Varshalovich, D. A., 2015, *MNRAS*, 448, 280

Komatsu, E. et al., 2011, *ApJS*, 192, 18

Landoni, M., Falomo, R., Treves, A., Scarpa, R., Farina, E. P., 2016, *MNRAS*, 457, 267

Laursen, P., Razoumov, A. O., Sommer-Larsen, J., 2009, *ApJ*, 696, 853

Lehnert, M. D., Becker, R. H., 1998, *A&A*, 332, 514

Liske, J., Williger, G. M., 2001, *MNRAS*, 328, 653

Maiolino, R. et al., 2012, *MNRAS*, 425, 66

Marshall J. L. et al., 2008, in McLean I. S., Casali M. M., eds, *Proc. SPIE Vol. 7014, Ground-based and Airborne Instrumentation for Astronomy II. SPIE*, Bellingham, p. 701454

Martin, P. G., 1988, *ApJS*, 66, 125

Martin, D. C., Chang, D., Matuszewski, M., Morrissey, P., Rahman, S., Moore, A., Steidel, C. C., Matsuda, Y., 2014, *ApJ*, 786, 107

Møller, P., Warren, S. J., Fall, S. M., Jakobsen, P., Fynbo, J. U., 2000, *The Messenger*, 99, 31

North, P. L., Courbin, F., Eigenbrod, A., Chelouche, D., 2012, *A&A*, 542, 91

Noterdaeme, P., Laursen, P., Petitjean, P., Vergani, S. D., Mauerreira, M. J., Ledoux, C., Fynbo, J. P. U., López, S., Srianand, R., 2012, *A&A*, 540, 63

Ofengeim, D. D., Balashev, S. A., Ivanchik, A. V., Kaminker, A. D., Klimenko, V. V., 2015, *Ap&SS*, 359, 26

Pâris, I. et al., 2011, *A&A*, 530, 50

Pâris, I. et al., 2014, *A&A*, 563, 54

Péroux, C., Quiret, S., Rahmani, H., Kulkarni, V. P., Epinat, B., Milliard, B., Straka, L. A., York, D. G., Rahmati, A., Contini, T., 2016, *MNRAS*, 457, 903

Petitjean, P., Rauch, M., Carswell, R. F., 1994, *A&A*, 291, 29

Petitjean, P., Pécontal, E., Valls-Gabaud, D., Charlot, S., 1996a, *Nature*, 380, 411

Petitjean, P., Theodore, B., Smette, A., Lespine, Y., 1996b, *A&A*, 313, 25

Petitjean, P., Vergani, S. D., 2011, *CRPhy*, 12, 288

Prescott, M. K. M., Dey, A., Jannuzi, B. T., 2013, *ApJ*, 762, 38

Prochaska, J. X., Hennawi, J. F., Herbert-Fort, S., 2008, *ApJ*, 675, 1002

Prochaska, J. X., Hennawi, J. F., 2009, *ApJ*, 690, 1558

Quiret, S. et al., 2016, preprint (arXiv:1602.02564)

Ryan-Weber, E. V., Pettini, M., Madau, P., Zych, B. J., 2009, *MNRAS*, 395, 1476

Rix, S. A., Pettini, M., Steidel, C. C., Reddy, N. A., Adelberger, K. L., Erb, D. K., Shapley, A. E., 2007, *ApJ*, 670, 15

Rubin, K. H. R., Prochaska, J. X., Koo, D. C., Phillips, A. C., 2012, *ApJ*, 747, 26

Schlegel, D. J., Finkbeiner, D. P., Davis, M., 1998, *ApJ*, 500, 525

Shapley, A. E., Steidel, C. C., Pettini, M., Adelberger, K. L., 2003, *ApJ*, 588, 65

Shull, J. M., Danforth, C. W., Tilton, E. M., 2014, *ApJ*, 796, 49

Shull, J. M., Moloney, J., Danforth, C. W., Tilton, E. M., 2015, *ApJ*, 811, 3

Silk, J., Rees, M. J., 1998, *A&A*, 331, 1

Simcoe, R. A., Sargent, W. L. W., Rauch, M., 2004, *ApJ*, 606, 92

Srianand, R., Hussain, T., Noterdaeme, P., Petitjean, P. et al., 2016, *MNRAS*, 460, 634

Steidel, C. C., Sargent, W. L. W., Dickinson, M., 1991, *AJ*, 101, 1187

Steidel, C. C., Adelberger, K. L., Shapley, A. E., Pettini, M., Dickinson, M., Giavalisco, M., 2000, *ApJ*, 532, 170

Steidel, C. C., Erb, D. K., Shapley, A. E., Pettini, M., Reddy, N., Bogosavljevic, M., Rudie, G. C., Rakic, O., 2010, *ApJ*, 717, 289

Tytler, D., Fan, X.-M., 1992, *ApJS*, 79, 1

Verhamme, A., Schaerer, D., Maselli, A., 2006, *A&A*, 460, 397

Verhamme, A., Schaerer, D., Atek, H., Tapken, C., 2008, *A&A*, 491, 89

Vernet, J. et al., 2011, *A&A*, 536, 105

Villar-Martín, M., Humphrey, A., De Breuck, C., Fosbury, R., Binette, L., Vernet, J., 2007, *MNRAS*, 375, 1299

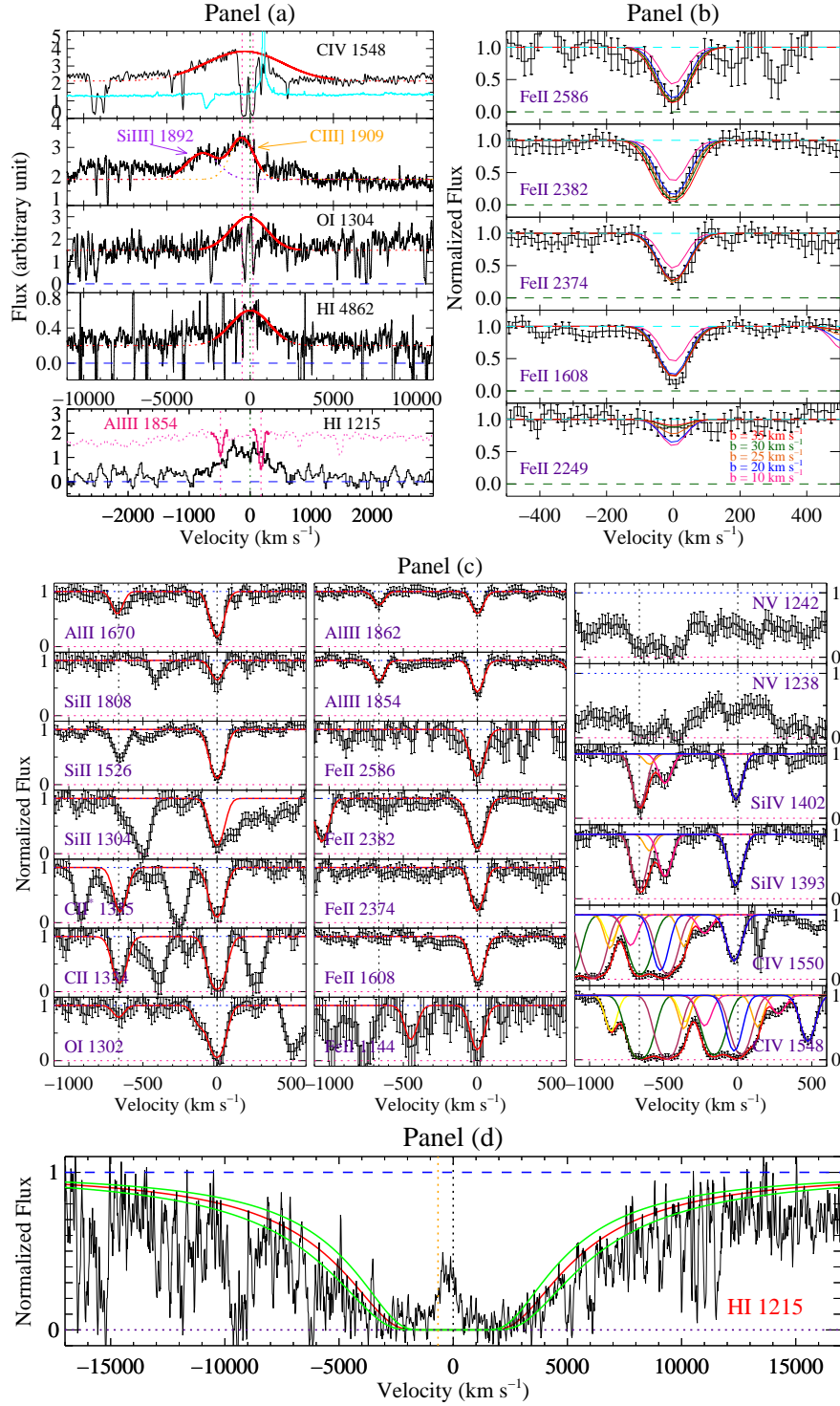
Vladilo, G., Centurión, M., Bonifacio, P., Howk, J. C., 2001, *ApJ*, 557, 1007

Weidinger, M., Møller, P., Fynbo, J. P. U., 2004, *Nature*, 430, 999

Weidinger, M., Møller, P., Fynbo, J. P. U., Thomsen, B., 2005, *A&A*, 436, 825

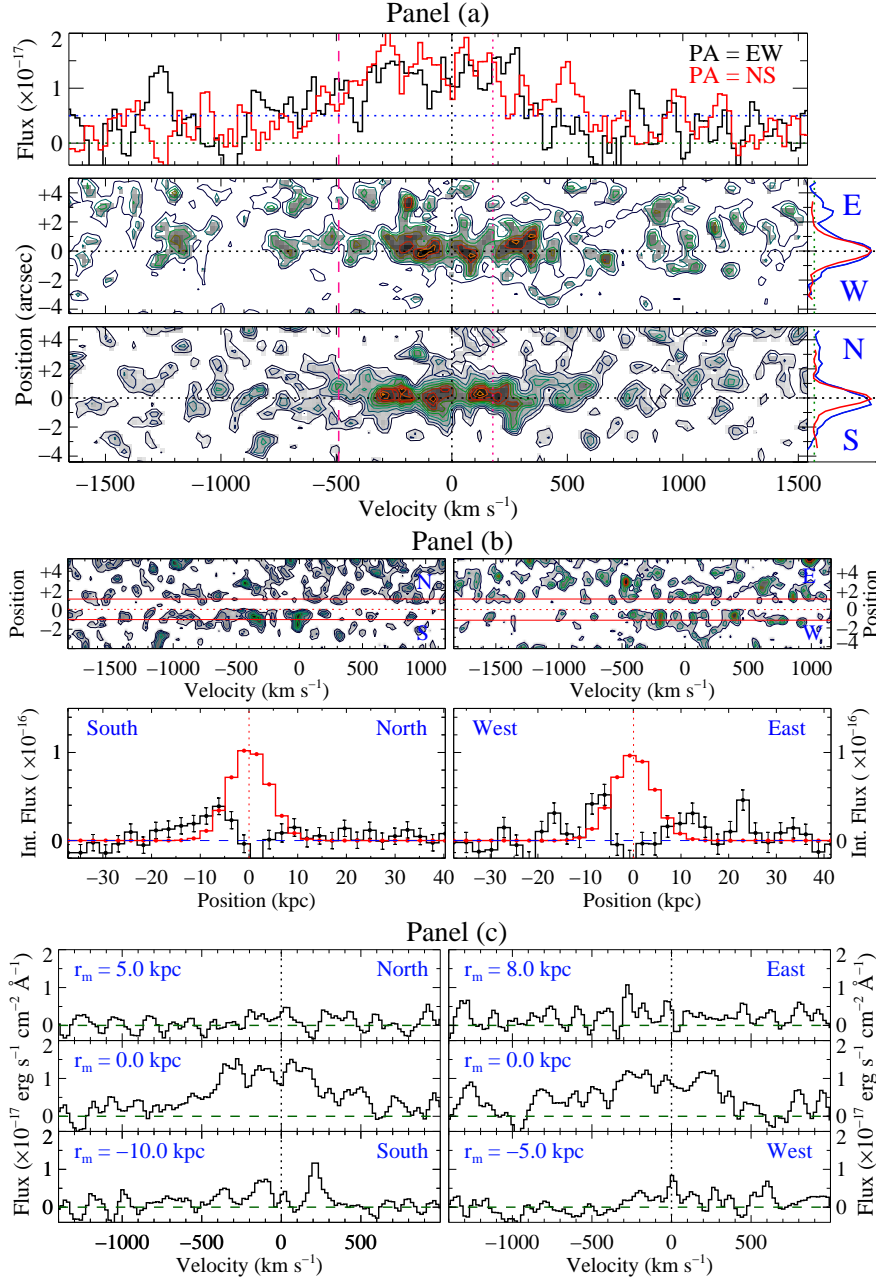
Yang, Y., Zabludoff, A. I., Davé, R., Eisenstein, D. J., Pinto, P. A., Katz, N., Weinberg, D. H., Barton, E. J., 2006, *ApJ*, 640, 539

## APPENDIX A: FIGURES A1 TO A8

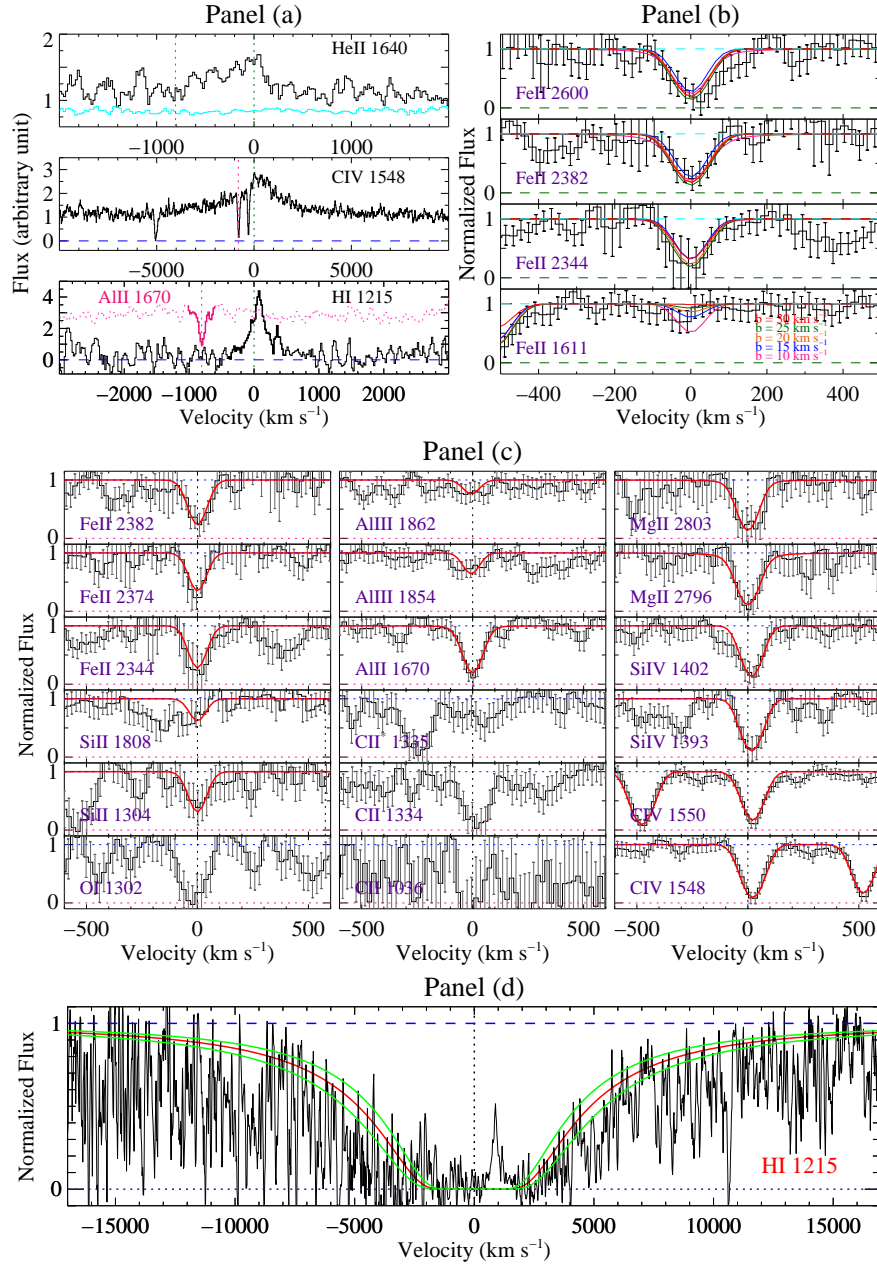


**Figure A1.** Same as Fig. 1 but for the quasar J0953+0349 with  $z_{\text{em}} = 2.5940$  and  $z_{\text{abs}} = 2.5961$ . The H I  $\lambda 4862$  spectrum in Panel (a) is from XSHOOTER observation.

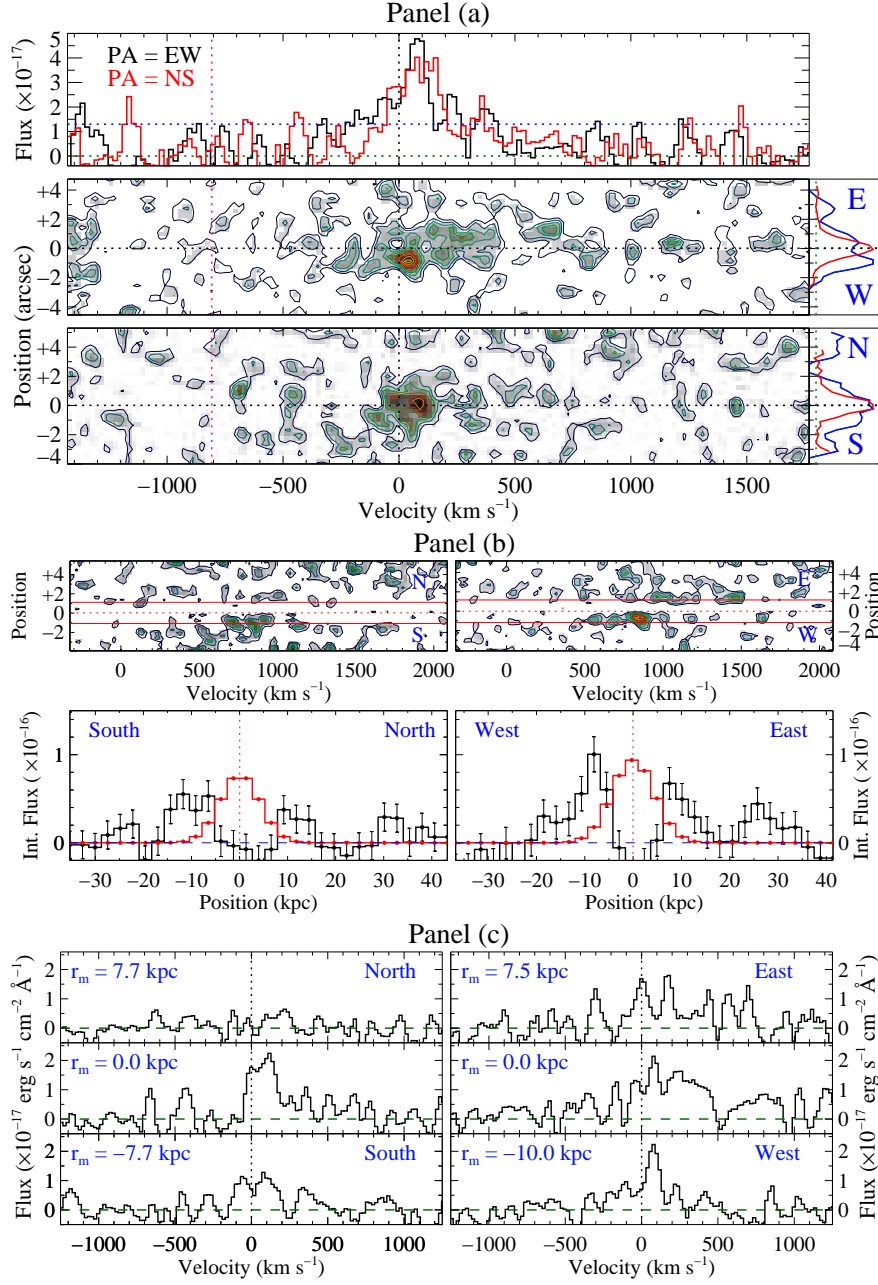




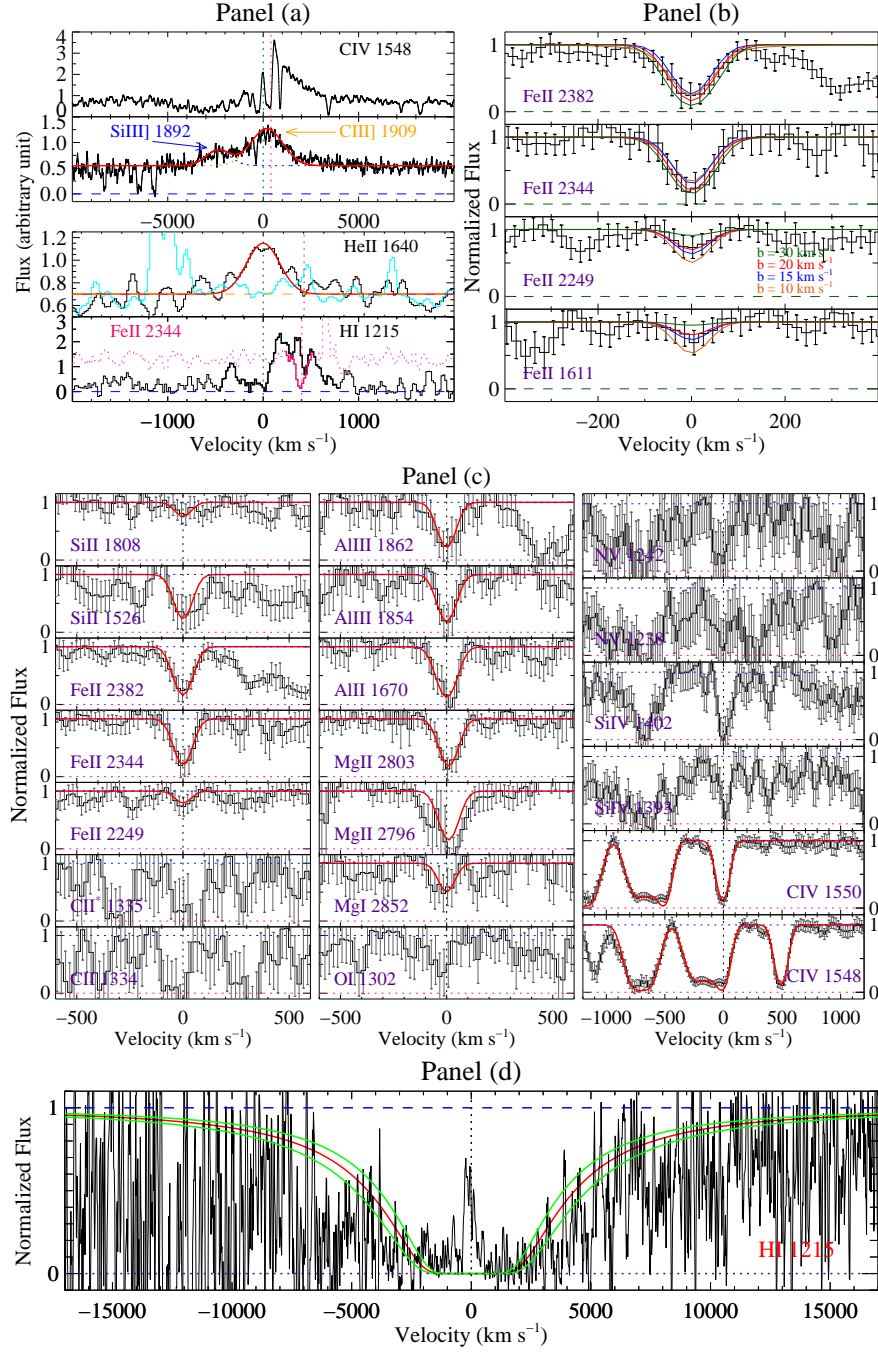
**Figure A2.** Same as Fig. 2 but for the quasar J0953+0349. The zero velocity is at  $z_{\text{em}} = 2.5940$ . In panel (a), the pink dotted lines mark the position of the DLA at  $z_{\text{abs}} = 2.5961$  and the pink dashed lines show the position of the absorber at  $z_{\text{abs}} = 2.5880$ . In panels (a) and (b) the outermost contour along PA=NS (resp. PA=EW) corresponds to a flux density of  $9.10 \times 10^{-20}$  (resp.  $1.36 \times 10^{-19}$ )  $\text{erg s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}$  and each contour is separated by  $9.10 \times 10^{-20}$  (resp.  $1.36 \times 10^{-19}$ )  $\text{erg s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}$  from its neighboring contour.



**Figure A3.** Same as Fig. 1 but for the quasar J1058+0315 with  $z_{\text{em}} = 2.3021$  and  $z_{\text{abs}} = 2.2932$ .

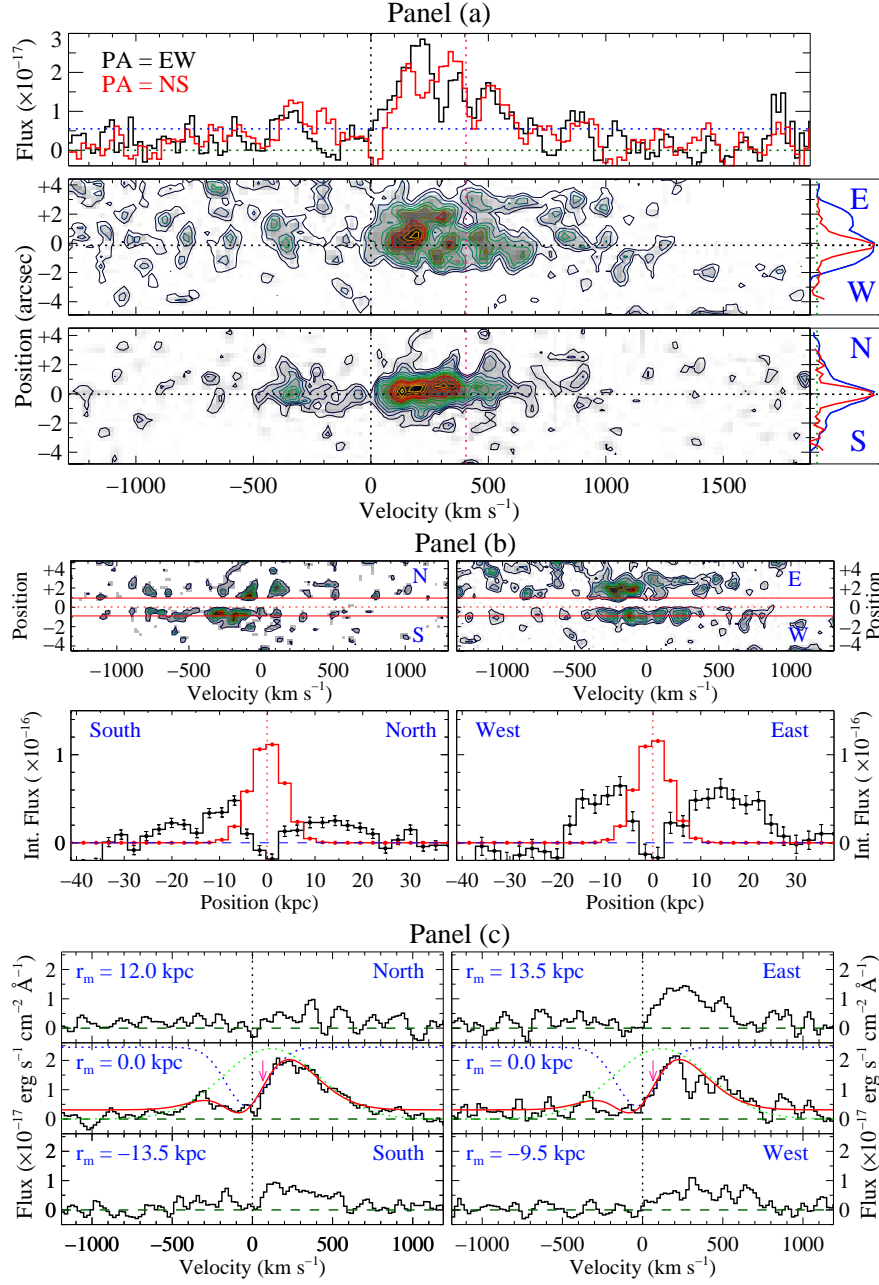


**Figure A4.** Same as Fig. 2 but for the quasar J1058+0315. The zero velocity is at  $z_{\text{em}} = 2.3021$ . In panel (a), the pink dotted lines mark the position of the DLA with  $z_{\text{abs}} = 2.2932$ . In panels (a) and (b) the outermost contour along PA=NS (resp. PA=EW) corresponds to a flux density of  $2.94 \times 10^{-19}$  (resp.  $3.36 \times 10^{-19}$ ) erg s $^{-1}$  cm $^{-2}$  Å $^{-1}$  and each contour is separated by  $2.94 \times 10^{-19}$  (resp.  $3.36 \times 10^{-19}$ ) erg s $^{-1}$  cm $^{-2}$  Å $^{-1}$  from its neighboring contour.

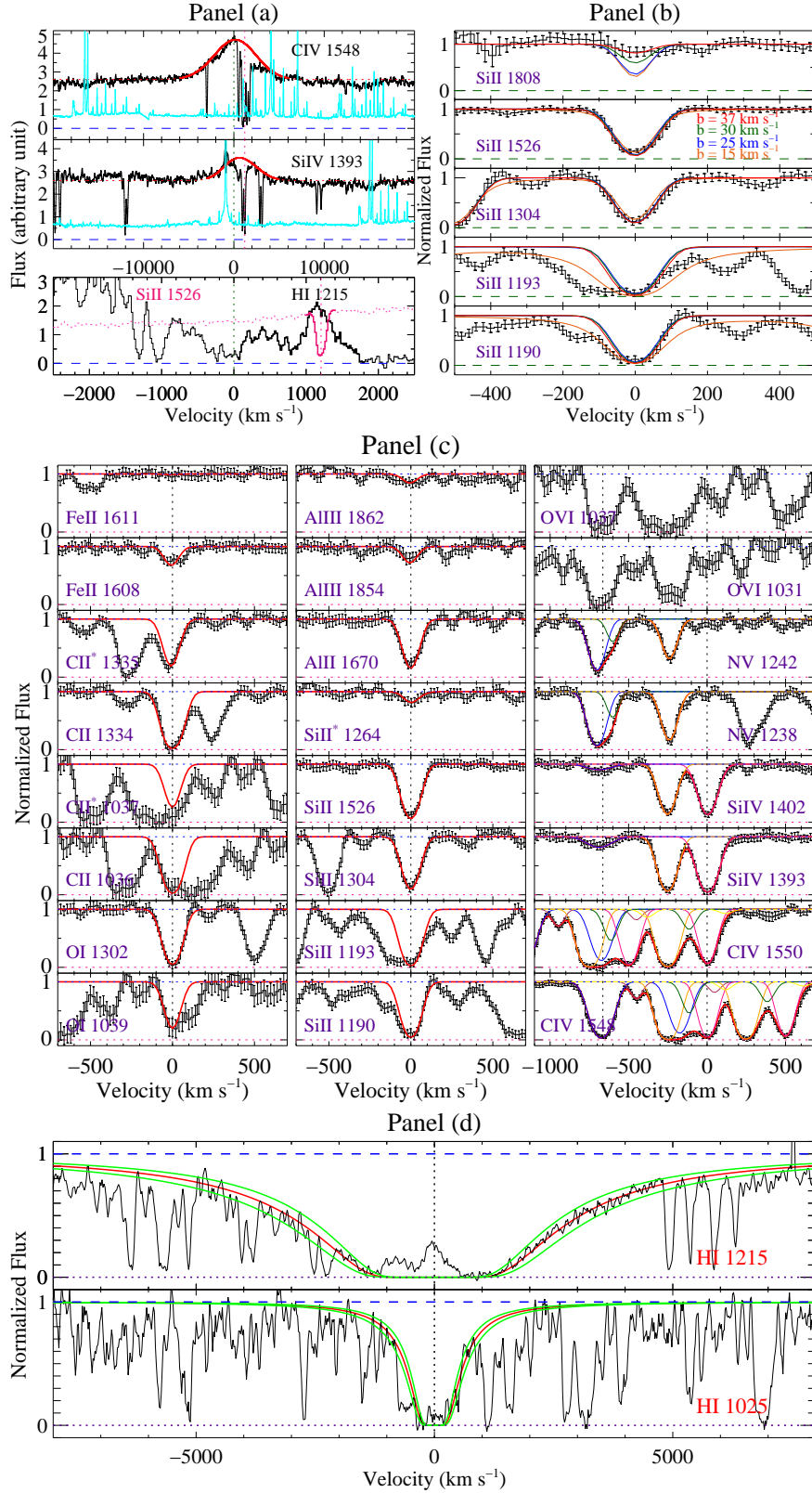


**Figure A5.** Same as Fig. 1 but for the quasar J1154-0215 with  $z_{\text{em}} = 2.1810$  and  $z_{\text{abs}} = 2.1853$ .

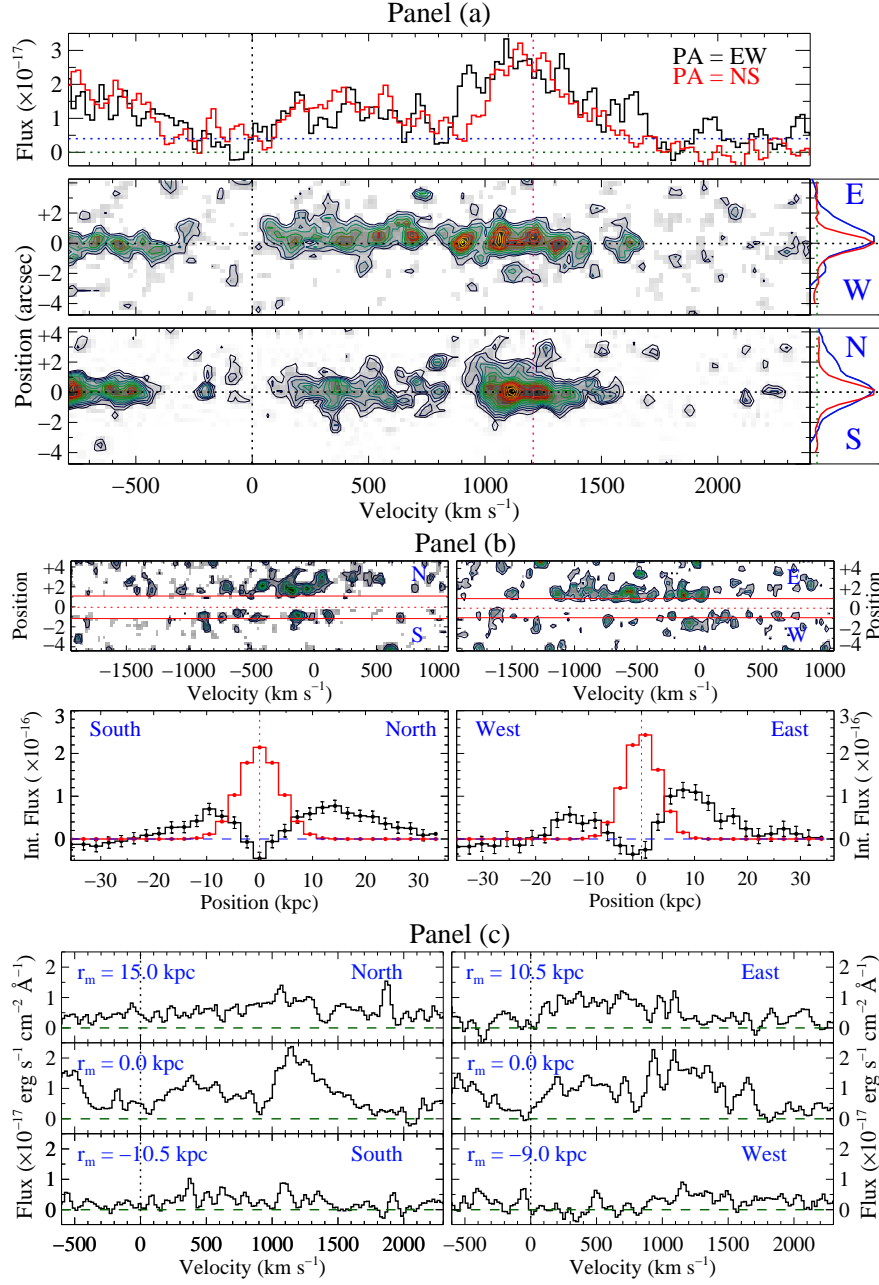




**Figure A6.** Same as Fig. 2 but for the quasar J1154-0215. The zero velocity is at  $z_{\text{em}} = 2.1810$ . In panel (a), the pink dotted lines mark the position of the DLA with  $z_{\text{abs}} = 2.1853$ . In panels (a) and (b) the outermost contour along PA=NS (resp. PA=EW) corresponds to a flux density of  $1.60 \times 10^{-19}$  (resp.  $1.29 \times 10^{-19}$ )  $\text{erg s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}$  and each contour is separated by  $8.00 \times 10^{-20}$  (resp.  $1.29 \times 10^{-19}$ )  $\text{erg s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}$  from its neighboring contour. See the text for the description of the red solid line, and the blue and green dotted lines shown in panel (c).



**Figure A7.** Same as Fig. 1 but for the quasar J1253+1007 with  $z_{\text{em}} = 3.0150$  and  $z_{\text{abs}} = 3.0312$ .



**Figure A8.** Same as Fig. 2 but for the quasar J1253+1007. The zero velocity is at  $z_{\text{em}} = 3.0150$ . In panel (a), the pink dotted lines mark the position of the DLA with  $z_{\text{abs}} = 3.0312$ . In panels (a) and (b) the outermost contour along PA=NS (resp. PA=EW) corresponds to a flux density of  $2.49 \times 10^{-19}$  (resp.  $2.26 \times 10^{-19}$ ) erg s<sup>-1</sup> cm<sup>-2</sup> Å<sup>-1</sup> and each contour is separated by  $8.30 \times 10^{-20}$  (resp.  $1.13 \times 10^{-19}$ ) erg s<sup>-1</sup> cm<sup>-2</sup> Å<sup>-1</sup> from its neighboring contour.